Effects of CCA Treatment and Re-drying on the Mechanical Properties of Radiata Pine

by

Rolando S. Uy, Jr.

Thesis submitted for the degree of Master of Science
at the Australian National University

Department of Forestry
Australian National University

July, 1993

DECLARATION

The work described in this thesis has been carried out and composed by the undersigned at the Department of Forestry in the Australian National University, Canberra, ACT. Any assistance received is acknowledged.

Candidate ....
R S Uy Jr.

Supervisor
of Studies ....PEvans..........
Dr P. D. Evans

July , 1993

ACKNOWLEDGEMENTS

I gratefully acknowledge and give thanks

To Dr Philip D. Evans for his supervision of this thesis and Mr Peter Beutel for his assistance during the conduct of experiments.

To the Australian International Development Assistance Bureau (AIDAB) and the M S U-Iligan Institute of Technology for their financial assistance.

To Mr John Carson, Mr Stephen Bolden and Mr Stephen Holtorf of the National Association of Forest Industries Ltd.(NAFI) and CSR Softwoods at Tumut, NSW for providing the structural size timber specimens.

To Koppers Australia at Hume, ACT and Mr David Flanagan for providing the CCA solution and for allowing me access to their equipment for the determination of CCA retentions.

To Mr Ross Cunningham, Ms Christine Donnelly and Mr Andrew Robinson for statistical advice.

To Mr Ken Groves for his comments and suggestions on the kiln drying of timber specimens.

To the late Mr Don Stodart for his fatherly advice and for his suggestions on the design of experiments during the early part of the study.

To Dr Robin Wingate-Hill, Dr Malcolm Pettigrove and Dr Ann Gibson for sharing their time in reading the manuscript and for their constructive comments and suggested corrections.

To Mrs Judy Lejins, Mrs Paula Reid, Mrs Kathy Callen, Mrs Zhoza Smith, Mr Roland Jahnke, Mr John Marsh, Mr Geoff Mitchell, Mr Mauro Davanzo, Mr Eric Cziesso, Mr Gary Chalker, Mr Jamie Buckeridge, and Mr Peter Mitchell for their support and co-operation.

To Ms Florence Soriano, Ms Priscila Torrente, Ms Laureen Laurito, Ms Rosario Labaro, Mr Angelo Benedictos, Mr Ur Bala and Mr Rodolfo Montenegro for their assistance and encouragement.

And finally, to my wife Lolita and children Ujee, Ulee, Uvee, Umee and Udee for their love and understanding during the years spent on this study.

Rolando S. Uy, Jr.

July, 1993

ABSTRACT

The effects of copper-chrome-arsenic (CCA) treatment and re-drying at high and low temperatures on the modulus of elasticity (MOE) and modulus of rupture (MOR) of small clear-wood and structural size radiata pine (*Pinus radiata* D. Don) specimens was examined. The effect of CCA treatment and re-drying on the maximum crushing strength (MCS) of small clear-wood specimens was also examined.

Results show that in both small clear-wood specimens and structural size timber CCA treatment and air drying does not adversely affect MOE and MOR. Treatment retentions had a negligible effect on the MOE and MOR after re-drying. Low temperature kiln drying (71 °C DBT) of treated wood had no deleterious effect on MOE and MOR. High temperature drying (116 °C DBT) of small clear-wood specimens and structural size timber had no significant effect on the MOE, but significantly decreased the MOR.

MCS of small clear-wood treated specimens decreased slightly after air drying, but increased significantly when specimens were kiln dried at high temperature.

MOE and MOR of water treated structural size radiata pine timber increased after re-drying at low temperature, but showed small decreases after re-drying at high temperature (116 °C).

Evaluation of the effect of CCA treatment and re-drying on strength properties using percentile strength distributions gave higher strength losses or gains than using average values, particularly when results were compared at the 5th percentile, lower exclusion limit.

These findings indicate that CCA-Type C preservative treatment, regardless of retention level, followed by air or kiln drying at low temperature does not significantly reduce the strength and stiffness of F5 grade structural size radiata pine timber. However, re-drying of treated radiata pine timber at high temperature (116 °C and above) significantly reduces strength and stiffness and therefore high temperature drying of CCA treated radiata pine is not recommended.

TABLE OF CONTENTS

Chapter Three

General Experimental Methods

Chapter Four

Preliminary studies using small clear-wood specimens

Chapter Five

Effect of CCA treatment and re-drying at high temperature on the mechanical properties of small clear-wood radiata pine specimens

Chapter Six

Effect of CCA treatment and re-drying at high temperature on the modulus of elasticity and modulus of rupture of structural size radiata pine timber

Chapter Seven

Effect of CCA treatment and re-drying at low temperature on the modulus of elasticity and modulus of rupture of structural size radiata pine timber

Chapter Eight

Conclusions and Suggestions For Further Research

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

ABBREVIATIONS

ACT	Australian Capital Territory
ANU	Australian National University
AS	Australian Standard
ASTM	American Society for Testing and Materials
AWPA	American Wood Preservers Association
CCA	Copper-chrome-arsenic
CSR	Colonial Sugar Refining Co.
DBT	Dry-bulb Temperature
EMC	Equilibrium moisture content
FSP	Fiber saturation point
HTD	High-temperature drying
KAR	Knot-area-ratio
MC	Moisture content
MCS	Maximum Crushing Strength
MOE	Modulus of Elasticity
MOR	Modulus of Rupture
NSW	New South Wales
R	Retention
RH	Relative Humidity
SR	Strength ratio
SRSS	Strength ration select structural
TR	Target retention
USFPL	U.S. Forest Products Laboratory
WBT	Wet-bulb Temperature
WML	Work to maximum load
WPL	Work to proportional limit

Chapter One

INTRODUCTION

1.1 Timber seasoning and preservation practices in the wood processing industry

In Australia and New Zealand, technologies have been developed for radiata pine (*Pinus radiata* D. Don) to produce a reliable structural product that can be used with confidence [Kininmonth and Whitehouse, 1991]. Grading rules (AS 2858 - 1986), framing (AS 1684 - 1979) and design codes (AS 1720.1 - 1988), and other related standards have been developed for the quality control of radiata pine for structural and other purposes. These standards specify that the timber should be seasoned and protected against decay and deterioration. The preservative most commonly used to treat radiata pine is CCA (copper-chrome-arsenic), one of a number of acidic water-borne preservatives acceptable to Australian Standard AS 1604-1980 (*Preservative treatment for sawn timber, veneer and plywood*).

Structural timber treated with a water-borne preservative is dried twice before being put into service. The timber is dried prior to treatment to ensure adequate absorption and penetration of the preservative solution and after treatment, the timber is dried again with the same objective as that of normal seasoning of green timber [Kininmonth, 1958].

Timber is normally seasoned for the following reasons:

(1) Wood when dry and in equilibrium with the surrounding atmosphere shows little tendency to shrink, swell, warp or split;

(2) Wood when dry (below 20% MC) is not subject to deterioration by fungi or bacteria;

(3) Wood when dry can be easily nailed, glued or finished with varnishes and paints;

(4) Most strength properties of wood increase as wood is dried;

(5) Removal of water from wood reduces wood weight and volume thus reducing handling and transport costs.

Details of these improvements are well-documented in textbooks of wood technology and timber handbooks (Panshin and de Zeeuw, 1980; Wallis, 1970). Drying of CCA treated timber also ensures that the preservative is `fixed' within the wood.

Good preservative treatment and proper seasoning practices should ensure a material of good quality. Ideally, seasoning should remove only the unwanted moisture from wood. Similarly, a good preservative treatment should only bond to the wood elements to protect them from decay organisms. Neither treatment process should degrade or weaken the material.

1.2 Strength losses in CCA treated timber

While one of the aims of timber preservation is to protect wood from decay without degrading the wood during and after treatment, there are reports of strength losses in CCA-treated timber after re-drying [Barnes and Mitchell, 1984; Knuffel, 1985; Winandy, *et al.,* 1985]. Users of CCA-treated radiata pine are reported to be concerned about these strength losses [Mackay, 1973]. Studies have shown that CCA-treated timber re-dried at high temperatures (i.e., above 100 °C) may suffer large strength losses. Treated timber re-dried at low temperature (i.e., air drying and conventional kiln drying) showed small strength losses [Barnes, 1986; Winandy, 1988]. However, strength losses are also reported in timber treated to high CCA retentions (~ 40.0 kg m^{-3}) after air drying [Bendtsen, *et al.,* 1983]. It is likely that CCA treatment at high retentions (e.g. > 16.0 kg m^{-3}) and re-drying at high temperatures (e.g. > 100 °C) would have even greater degradative effects on the mechanical properties of wood.

There are some inconsistencies in the literature regarding the effect of CCA treatment and re-drying on the strength properties of timber. For example, Bendtsen, *et al.*, (1983) reported a 12% reduction in MOR of small clear-wood longleaf pine (*Pinus palustris* Mill.) treated to a retention of 16 kg m^{-3} and re-dried at 60 °C, but Winandy, *et al.*, (1985) did not find significant strength losses in similarly treated and re-dried small clear-wood specimens. Furthermore, Winandy and Boone (1988) found no significant effects of CCA treatment (R = 9.6 kg m^{-3}) on the MOR of structural size timber after air drying, while Winandy (1989) in a similar study found a reduction of 7 to 13% in the MOR of CCA-treated air dried structural size timber.

There is insufficient evidence to make generalisations concerning the effects of CCA treatment and re-drying on the mechanical properties of wood and particularly structural size timber. Strength losses in CCA-treated radiata pine after drying have not been examined in detail and further work is necessary to determine the effect of different treatment retentions and drying temperatures on strength losses.

1.3 Aim of the study

The main aim of this study was to determine whether CCA treatment and kiln drying after treatment reduces the mechanical properties of radiata pine. Particular emphasis was placed on the influence of CCA retention and re-drying temperature on mechanical properties. The experiments reported in each chapter have specific aims which relate to the main aim of this study. A secondary aim of this study was to examine the relationship between the strength changes in small clear-wood specimens after CCA treatment and re-dying and those in larger structural timber after similar treatment.

1.4 Scope of study

There is increasing use of re-dried CCA-treated radiata pine, yet the effects of CCA treatment and re-drying on the mechanical properties of radiata pine have not been fully evaluated. Most studies of the effect of CCA treatment and re-drying on the mechanical properties of timber have used small clear-wood specimens. Since there are suggestions that strength losses due to CCA treatment and re-drying interact with wood type and specimen size [Winandy and Boone, 1988; LeVan and Winandy, 1990], this study used both defect-free small clear-wood specimens and structural size, defect-containing timber.

The study used only one structural grade of Australian grown radiata pine (*Pinus radiata* D. Don) and one CCA formulation. Radiata pine grade No.5 (F5) was selected because it is the grade most commonly used in Australia. Tanalith C-CCA was used because it is the most commonly used CCA formulation and most other studies of the effect of CCA treatment and re-drying on the strength properties of timber have also used this formulation.

To determine the effect of CCA treatment and re-drying on the mechanical properties of radiata pine, several experiments were carried out. These are briefly described in the next section (study outline). Experiments usually used two treatment retentions, low and high, but both retentions were above 12.0 kg m^{-3} since a previous study [Winandy, 1988] showed that retentions below this level had little effect on the mechanical properties of wood. The mechanical properties evaluated include two strength properties; modulus of rupture (MOR) and compression parallel to the grain or the maximum crushing strength (MCS), and one elastic property, the modulus of elasticity (MOE). MOR was used as it is a measure of the maximum strength of a beam and because it is one of the strength properties that is most deleteriously affected by CCA treatment and re-drying [Winandy, 1988]. MCS and MOE were used because they are important factors in the design of wooden structures. The mechanical properties of structural size radiata pine timber and small clear-wood specimens were calculated from data obtained by standard static bending and compression tests (ASTM D 198 and ASTM D 143).

1.5 Study outline

The study is presented in eight chapters. The introduction provides a rationale, statement of the problem, aim and scope of the study, as well as this study outline. Chapter Two reviews the literature and focuses on the effects of CCA treatment and re-drying on the strength properties of wood. Background information is presented to enable the reader to understand the thesis. Definition of terms are given in Appendix A. Chapter Three outlines the general experimental methods used, including descriptions of materials, preparation of specimens, treatment procedure, drying, conditioning and strength testing of specimens, methods of calculations of strength parameters and analysis of data.

The experiments were conducted in accord with the main aims of the study. Chapter Four examines the effects of CCA treatment and air drying, water treatment and air drying, and drying temperature on the MOR and MCS of small clear-wood radiata pine specimens. The effect of CCA treatment and re-drying at high temperature on the MOE, MOR and MCS of small-clear wood radiata pine specimens are examined in Chapter Five. The effects of CCA treatment and re-drying at high temperature, using two preservative retentions, on the MOE and MOR of structural size radiata pine timber is examined in Chapter Six. Chapter Seven examines the effect of a CCA treatment and re-drying at low temperature on the MOE and MOR of structural size radiata pine timber.

The findings of the experiments are summarized in Chapter Eight. Conclusions are given and their implications are discussed and a number of recommendations are then made.

Chapter Two

REVIEW OF THE LITERATURE

The literature concerning the factors affecting the mechanical properties of wood are voluminous, therefore this review focuses on the effects of CCA treatment and re-drying on the strength properties of wood. Background information which is necessary to understand the thesis is also included.

2.1 Structural nature of wood

Wood is a product of the metabolism of the living tree and it is sufficiently strong to support the standing tree. Wood is of far greater complexity than other major engineering materials such as steel, bricks and concrete and its properties are inherently variable. Furthermore, there are many different wood species and each exhibits different anatomical, physical and chemical characteristics. Regardless of its botanical origin, wood possesses some characteristics in common. These characteristics are reviewed by Panshin and de Zeeuw (1980).

Wood is composed of elongated, round or rectangular, tube-like cells. These cells have tapered ends which overlap with other cells. The majority of these cells are oriented parallel with the length of the tree. A smaller fraction of cells, called ray tissues, radiate from the center of the tree toward the bark and these cells interlock with longitudinal cells. The cell walls are made up of a mixture cellulose and hemicellulose which are bonded together by an aromatic polymer known as lignin. The latter provides rigidity to the wood structure. The cell wall is multi-layered consisting of cellulosic strands known as microfibrils. Details of the ultrastructural organization of the wood cell wall are given by Panshin and de Zeeuw (1980).

The structure and organization of wood cells gives wood its structural strength, but it also makes wood naturally anisotropic and accounts for the combination of elastic and plastic responses that occur when wood is subjected to applied forces.

2.2 Mechanical properties of wood

The term 'mechanical properties' refers to the various attributes of a material which describe its ability to sustain forces or loads and to resist deformation under an applied load. These are categorized into strength, elastic, and time-dependent properties (see Table 2.1). They are important criteria for the selection of wood for structural applications, especially, where strength is the primary consideration [USFPL, 1974; Haygreen and Bowyer, 1982].

The term strength is often used in a general sense to refer to all mechanical properties. According to Haygreen and Bowyer (1982), this can lead to confusion since there are many different types of strength and elastic properties. A wood species that is relatively strong with respect to one strength property may, when compared to a different species, be relatively weak in another property. It is important to be specific about the type of mechanical property being described. For the purpose of this review, the term strength is used in a general sense unless otherwise specified. This is because some of the literature reviewed did not specify the particular strength property being described. Some of the most important mechanical properties of wood are listed in Table 2.1, including a description of why or where the particular property is important.

2.3 Percentiles of property distribution and the concept of exclusion limits

A common statistical method of describing strength property values involves the construction of a frequency distribution of the data in a coordinate system either using a histogram or a frequency polygon. From these graphs, percentiles can be determined. For example, the nth percentile of the distribution is the score (property value) corresponding to a point on the scale of scores such that the nth percent of the

Table 2.1 Important mechanical properties of wood*

Properties	How or where this property is important
Strength properties	
Bending strength (MOR)	Determines the load a beam will carry.
Compression parallel to the grain (MCS)	Determines the load a short post or column will carry.
Compression perpendicular to the grain	Important in design of the connections between wooden members in a building and at the supports for a beam.
Tension strength parallel to the grain	Important for the bottom member (chord) in a wood truss and in the design of connections between structural members.
Tension perpendicular to the grain	Important in design of the connections between wood members in a building.
Shear strength parallel to the grain	Often determines the load-carrying capacity of short beams.
Toughness	A measure of the amount of work expended in breaking a small specimen in impact bending.
Side hardness	Relates to the resistance to denting, as for flooring.
Work to maximum load (WML)	A measure of the energy absorbed by a specimen as it is slowly bent.
Elastic properties	
Modulus of elasticity (MOE)	A measure of the resistance to bending, i.e., directly related to the stiffness of a beam. Also a factor in the strength of a long column.
Modulus of elasticity parallel to the grain (Young's modulus)	A measure of the resistance to elongation or shortening of a specimen under uniform tension or compression.
Resilience	A measure of the amount of energy absorbed when a piece is bent within its elastic range.
Rheological properties	
Creep	A measure of the additional time-dependent deformation that develops slowly after the load is applied and maintained for a long period of time.
Fatigue	The progressive damage and failure that occurs when a structure or part of it is subjected to repeated loads of a magnitude smaller than the static strength.

*Adapted from Haygreen and Bowyer (1982), and USFPL, (1974).

area of the histogram or polygon lies below an ordinate at that point. Details of this method of data representations are explained in Walker and Lev (1958). A simple way to show the percentile or ranking of scores in the distribution is to plot a cumulative percent curve, called an *ogive* (e.g., Figure 5.3a). Such a graph shows the scales of scores or property values on one axis (usually the vertical axis). The cumulative percent of the frequency below a given score is shown on the other axis (usually the horizontal axis). In effect, the graph depicts the variability of the data as indicated by the rank or relative position (percentile) of individual scores in the distribution.

The use of exclusion limits for strength properties came about in the interest of safety in the design of structures. To account for the natural variation of strength property values and to provide for safety in design, pieces of timber with a strength property of less than the actual strength of at least 95 percent of the pieces in that grade are excluded from the grade [USFPL, 1974]. Hence, the 5 percent lower exclusion limit is a focal point in design values [Barnes and Mitchell, 1984]. The exclusion limit is defined as a level of strength value below which a selected percentage (say, 5%) of the strength values are expected to fall and corresponds to a selected probability point (i.e., 0.05) from the frequency distribution of strength values [ASTM D 2555]. This value (exclusion limit) is used to obtain the 'safe' grade strength property by multiplying it by the minimum strength ratio permitted in the grade being considered [USFPL, 1974].

2.4 Factors affecting the mechanical properties of wood

2.4.1. Effects of moisture content (MC)

In general there is agreement in the literature that the moisture content of wood above the fiber saturation point (FSP) (i.e., above 30% MC) has no significant effect on strength properties. When wood dries below FSP, bound water is removed from sorption sites (hydroxyl groups) on the cellulosic microfibrils in the wood cell walls.

Adjacent microfibrils then move closer together and hydroxyl groups bond to each other through 'hydrogen bonding'. Macroscopically this is manifested as shrinkage of the wood. At the molecular level, the degree of cell-wall compactness increases causing wood strength to increase [Wangaard, 1966; Skaar, 1972]. Most studies have therefore shown that as MC decreases below FSP, most mechanical properties increase [Brown, *et al.*, 1952; Stamm, 1964; Skaar, 1972; Bodig, 1982; Haygreen and Bowyer, 1982; Bier, 1983]. While this trend seems to be the rule for most mechanical properties, some strength properties such as shock resistance and toughness increase directly as moisture content changes within the hygroscopic range (i.e., between 0% MC and FSP) [Panshin and de Zeeuw, 1980].

Bodig (1982) comprehensively discussed the effects of moisture on the static, dynamic and long-term behavior of wood, with particular emphasis on structural members. In accord with Madsen and Eng (1984), Bodig recognized the difference between the effect of moisture on the strength of small clear-wood and its effects on structural size timber. On average, for similar decreases in MC, the strength of small clear-wood specimen increases to a greater extent than for structural sized timber. It was also observed that in some structural sized timber, strength properties decreased with a loss in MC below FSP [Gerhards, 1968; Bodig, 1982]. Variations in the effects of MC on the strength of different grades of dried timber were also reported. Lower grades, i.e., those containing larger growth defects often showed little or no increase in strength with decreases in MC below FSP [Gerhards, 1968].

2.4.2. Effects of drying

According to Thompson (1969a), investigations on the effect of heat (drying temperature) on wood strength date back to 1906. Since that time, numerous reports have dealt with this subject and these are found in textbooks on wood science and technology, wood handbooks and reviews of the literature [e.g., USFPL, 1974; Panshin and de Zeeuw, 1980; Desch and Dinwoodie, 1981; Haygreen and Bowyer, 1982; Beall, 1982; Salamon, 1969; Gerhards, 1982]. The findings can be summarized as follows;

Drying can adversely affect the mechanical properties of wood in two ways. The first is associated with excessive internal stresses arising from uneven shrinkage caused by large moisture gradients and differential shrinkage associated with the anisotropic nature of wood. In structural sized timber these effects can result in checking and splitting especially in areas of distorted grain, such as around knots. The tendency of wood to check is especially pronounced where inappropriate and inadequately controlled drying temperatures and relative humidities are used [Mottet, 1982; Thompson, 1982]. Secondly, heat involved in drying may catalyze hydrolytic and oxidative degradation of the wood cell-wall [Mottet, 1982].

Salamon (1969) and Gerhards (1982) have extensively reviewed the literature concerning the effects of drying on the strength properties of wood. Salamon (1969) reviewed the effects of high temperature drying on the quality and mechanical properties of softwood and hardwood timber. Gerhards (1982) reviewed the immediate effect of drying on several mechanical properties of small clear-wood specimens.

Most strength properties of wood decrease when it is heated and increase when it is cooled. This effect is immediate and is approximately linear at a constant MC between temperatures of -50 °C and 150 °C [Haygreen and Bowyer, 1982; LeVan and Winandy, 1990]. The immediate effect is defined as the change in properties that occur when wood is heated or cooled and then tested in that condition [USFPL, 1974]. Short term exposure to temperatures below 100 °C in an ordinary atmosphere (i.e., air drying or conventional kiln drying) has no permanent effect on strength properties [Beall, 1982]. However, prolonged exposure to temperatures in excess of 65.5 °C can cause permanent loss of wood strength [LeVan and Winandy, 1990]. The literature does not specify what short-term and prolonged exposure is.

It has been found that some wood species differ in the maximum temperature that they can tolerate before strength reductions occur. For example, for Douglas-fir

(*Pseudotsuga menziesii* (Mirb) Franco), a temperature of 59 °C was found to be the maximum kiln temperature that could be used without causing reductions in strength, particularly measures of toughness such as impact strength and work to maximum load (WML). Sitka spruce (*Picea sitchensis* (Carr.) Desc.) and western white pine (*Pinus monticola* Dougl.) were found to be capable of tolerating higher temperatures, up to 71 °C, without loss in strength [Mottet, 1982]. Repeated exposure to elevated temperature has a cumulative effect on wood strength. For example, at a given temperature (above 65.5 °C), the property loss will be about the same after six one - month exposure periods as it would after a single 6-month exposure period [USFPL, 1974].

High-temperature drying (HTD), generally in the range of 105 °C to 115 °C, is reported to cause significant reductions of 7% to 20% in the bending strength of Douglas-fir, western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and eastern spruce (*Picea spp.*) [Gerhards, 1979; Kozlik, 1976 & 1982; Huffman, 1977]. The properties most severely affected by HTD were toughness and WML, while MOE was the least affected, if at all. MOR, MCS, and shear parallel to the grain were usually intermediately affected [Mottet, 1982]. In contrast, some species, such as southern pines (*Pinus* spp.) [Koch, 1971; Yao and Taylor, 1979; Price and Koch, 1980], yellow poplar (*Liriodendron tulipifera* L.) [Gerhards, 1983], and radiata pine [Hillis, 1984] have shown little or insignificant losses in bending strength when subjected to HTD.

2.4.3. **Effects of acids and salts**

Studies have shown that aqueous solutions of acids and salts can reduce wood strength depending upon the concentration of acids or the solubility of the salts, pH, exposure time and temperature [Browning, 1963; Stamm, 1964; Wangaard, 1966; Kass, *et al.*, 1970; Thompson, 1969b & 1982]. Different wood species vary in their chemical composition and also in their resistance to attack by chemicals. In general, softwood species show greater resistance to chemical degradation than hardwood species [Wangaard, 1966; Panshin and de Zeeuw, 1980].

Wangaard (1966), treated a group of hardwoods and softwoods, including Douglas-fir and Caribbean pine (*Pinus caribaea* Mor.) with 2% or 10% hydrochloric acid (HCl), and sodium hydroxide (NaOH) solutions for 4 days at 50°C, and for 32 days at 20°C. He found that NaOH had a greater deleterious effect on MOR than HCl. HCl had a greater effect on WML, particularly at a concentration of 10%. The hardwoods showed greater strength losses than the softwoods, while among the softwoods, the pines showed smaller strength losses than Douglas-fir. A study on the resistance of southern pines to chemical degradation (Thompson, 1969b), also revealed results that were consistent with those of Wangaard (1966).

Kass *et al.*, (1970) found only minor losses in the MOR of hardwoods and softwoods after soaking in 2% HCl for 32 days at 20 °C, but specimens soaked in 10% HCl for 4 days at 50 °C showed losses in MOR of up to 70%. Kollmann (1936), cited by Stamm (1964), showed only a small weakening effect when six air-dry wood species were soaked in acetic and lactic acids at concentrations of 2%, 5%, and 10% for 4 weeks. Hydrochloric, sulfuric, and nitric acids showed a significant weakening effect on hardwoods only at concentrations of 10%. Permanent losses in strength of wood may be caused by prolonged contact with hydrolytic chemicals such as strong acids and highly acidic or alkaline salts [Stamm, 1964].

Exposure to some chemicals can increase wood strength. Erickson and Rees (1940) found that the maximum crushing strength of wood was increased after it was soaked in certain salt solutions. They reported that soaking sapwood of red pine (*Pinus resinosa* Ait.) in chloride salts at concentrations of 25.5% (KCl), 26.3% (NaCl), 38.6% ($MnCl_2$), 32.6% ($MgCl_2$), 39.6% ($CaCl_2$), and 43.3% (LiCl) for prolonged periods (31 to 50 days) increased MCS by up to 46%. Only 68.3% thiocyanate and 59.1% iodide salt solutions caused decreases (10 - 14%) in MCS.

In general, exposure of wood to dilute acids and salts at ambient temperatures within the pH range 3 to 10 has little degradative effect on the strength properties of wood [Stamm, 1964; Thompson, 1969b].

2.5 Effects of CCA treatment and re-drying on the strength properties of wood

CCA preservatives, consist of aqueous mixtures of salts or oxides of copper, chromium and arsenic. They are the most commonly used water-borne preservatives for the treatment of timber against biological attack. There are a number of different types of CCA preservatives and these differ in their chemical composition (see Appendix C for details). Connell and Nicholson (1990) reviewed the use of CCA and discussed the use of the various types of CCA formulations. CCA is impregnated into wood at concentrations of 0.5 - 10% so that, depending on the end use of the treated timber, the wood achieves specified retentions (see Appendix B). CCA-treated wood is characterized by cleanliness, paintability, and resistance to environmental leaching and biological deterioration and therefore CCA is the preferred treatment for timber in ground contact [Winandy, *et al.*, 1985]. While CCA is an excellent preservative, there is concern that re-drying after treatment, especially at high temperatures, may adversely affect the mechanical properties of wood [Mackay, 1973; Barnes and Mitchell, 1984; Winandy, *et al.*, 1985]. Most CCA formulations in use are sufficiently acidic to hydrolyze wood, and heating during subsequent drying of treated material can result in significant strength losses [Barnes and Mitchell, 1984; Winandy, *et al.*, 1983; Barnes, 1986].

2.5.1. Effects of CCA treatment alone

Some investigators have reported little effect of CCA treatment (after air drying) on wood strength. Lew and Dost (1983) found that CCA treatment (R =12.6 kg m^{-3}) did not reduce the hardness of ponderosa pine (*Pinus ponderosa* Dougl.) pole sections. Bariska, *et al.*, (1988) reported no loss in strength of CCA-treated radiata pine (R = 6 kg m^{-3}) poles when they were tested in tension parallel to the grain, but treated poles had a different failure mode compared to untreated poles. For treated samples the mode of failure always occurred at the early/latewood interface of growth rings. This was not the case for the untreated samples which failed "in a normal manner". Donnelly and Siemon (1989) found no significant effect of CCA treatment (retention not reported) on the MOR and MOE of radiata pine poles. Evans, *et al.*, (1991) reported that the effect of various CCA-Type C preservative formulations (R = 12.0 kg m^{-3}) on the impact bending strength of slash pine (*Pinus elliottii* Engelm.) posts was of little practical significance. Similarly, Wazny and Krajewski (1992) reported that CCA treatment of radiata pine blocks at retentions ranging from 0.15 to 5.0 kg m^{-3} and subsequent storage for three years did not have any significant effect on the compression strength parallel to the grain.

Other researchers have reported deleterious effects of CCA treatment on the strength properties of wood and wood products. For example, Boggio and Gertjejansen (1982) found that CCA treatment (R = 3.2 - 6.4 kg m^{-3}) reduced the MOR of aspen (*Populus spp.*) waferboard made with resole resin by 26 - 50% after aging. Wood, *et al.*, (1980) found 32% and 23% reductions, respectively, in the toughness and WML of specimens cut from southern pine pole sections treated with a CCA-Type C preservative to a retention of 40.0 kg m^{-3}. Knuffel (1985) found that the 5th percentile of compression parallel to grain in various grades of South African pine (*Pinus patula*) was reduced by 16% after CCA treatment (R =12 kg m^{-3}). These results suggest that the effect of CCA treatment on the mechanical properties of wood varies according to the strength property evaluated, the retention of preservative, and the species of wood or type of wood product. It appears that MOE, hardness and impact bending strength are not significantly affected by preservative treatment up to a retention of 12.0 kg m^{-3}. Higher treatment retentions (~ 40 kg m^{-3}) have a definite weakening effect on toughness and WML. Among the species examined, radiata pine exhibited the greatest resistance to CCA treatment (up to 12.0

kg m^{-3}). Wood composites such as waferboard appear to lose significant strength after CCA treatment.

2.5.2. Effects of CCA treatment and re-drying

2.5.2.1. Small clear-wood specimens

Studies of the effect of CCA treatment and re-drying on the mechanical properties of small clear-wood specimens indicate that strength losses result from an interaction of CCA retention and drying temperature. A summary of these studies is presented in Table 2.2. Winandy, *et al.*, (1985) concluded that MCS, MOE, MOR, and WML of small clear-wood samples of longleaf pine and slash pine were not affected by combinations of CCA retention levels, up to 16.0 kg m^{-3} and drying temperatures up to 60 °C. However, at retention levels up to 16.0 kg m^{-3} and a drying temperature of 82 °C, MOR and WML were reduced by 11% and 37%, respectively. They also reported that at a CCA retention of 40.0 kg m^{-3} and a drying temperature of 82 °C, MCS was increased by 9%, MOR was reduced by 12%, and WML was reduced by 46%. MOE was not affected. When the drying temperature was increased to 104.4 °C, MCS, MOR and WML decreased by 9, 30, and 68%, respectively. Again MOE was not affected.

In another study, Winandy, *et al.*, (1983) found that the toughness of small clear-wood southern pine (longleaf and slash pine) specimens was significantly reduced, after treatment with a CCA-Type C preservative followed by re-drying in an oven at 87.8 °C. Toughness was reduced by 16 to 23% for specimens treated to a retention of 9.6 kg m^{-3} and by 36 to 47% for specimens treated to a retention of 40.0 kg m^{-3}. Mitchell and Barnes (1986) found similar losses in toughness of high-temperature and conventionally dried small clear-wood southern pine samples treated with a CCA-Type A preservative to a retention of 4.8 kg m^{-3}. Siemon (1979) reported a 10% reduction in the MOR of small clear-wood Caribbean pine specimens after treatment with CCA (R = 16.0 kg m^{-3}) followed by HTD at 120 °C DBT / 90 °C

Table 2.2 A summary of studies undertaken to evaluate the effect of CCA treatment and re-drying on the strength properties of small clear-wood specimens

Author	Species (Chemical)	C CA retention (kg m^{-3})	Re-drying temp. (°C)	Strength loss (%)*					
				MOE	MOR	WML	MCS	WPL	Toughness
		4.0	Air	N S	N S				
Bendtsen			60.0	N S	N S				
Gjovik	Southern	9.6	Air	N S	NS				
and	pine		60.0	N S	10.0				
Verrill		16.0	Air	N S	N S				
(1983)	(CCA-A)		60.0	N S	12.0				
		40.0	Air	N S	19.0				
			60.0	N S	16.0				
Siemon	Caribbean								
(1979)	pine	16.0	120.0	N S	10.0				
	(CCA-C)								
		4.0	26.6-60	N S	N S	N S	N S		
Winandy		6.4	26.6-60	N S	N S	N S	N S		
Boone	Southern	9.6	26.6-60	N S	N S	N S	N S		
and	pine	16.0	26.6-60	N S	N S	N S	N S		
Bendtsen		4-16.0	82-104.4	N S	11.0	37.0	N S		16 - 23
(1983)	(CCA-C)	40.0	26.6-60	N S	N S	27.0	+15.0		
&		40.0	82.2	N S	12.0	46.0	+ 9.0		36 - 47
(1985)		40.0	104.4	N S	30.0	68.0	9.0		
		9.6	115.5	N S	9.7			N S	
	Southern	9.6	126.7	7.5	20.5			23.8	
Barnes	pine	9.6	137.8	12.9	32.9			43.6	
(1985)		24.0	115.5	N S	7.1			N S	
	(CCA-C)	24.0	126.7	11.0	11.9			10.2	
		24.0	137.8	10.0	36.9			44.1	
Mitchell	Southern								
and	pine	4.8	87.8	N S	11.0	N S		11.0	11.5
Barnes		4.8	115.5	N S	13.0	N S		N S	21.9
(1986)	(CCA-C)								

N S Not significant; + Significant increase
*Care should be taken when comparing strength loss figures since treatment and drying conditions vary greatly between studies.

WBT. MOE increased slightly (1.2%) after treatment and drying, but the increase was statistically insignificant.

Bendtsen, *et al.*, (1983) evaluated the change in mechanical properties of small clear-wood longleaf pine specimens after treatment with three types of water-borne preservatives at four retention levels using two post-treatment drying methods. For all combinations of treatments, the MOE of wood samples was not significantly affected. MOR was greatly reduced after treatment with a CCA-Type A preservative and re-drying. Strength losses after treatment with a CCA-Type B preservative followed by re-drying were smaller. This was attributed to the lower chromium content of the CCA-Type B preservative. Treatment with an ACA preservative (ammonical copper arsenate) reduced WML, but only at the highest retention used.

Mitchell and Barnes (1986) found no significant difference in the MOE of treated (R = 4.8 kg m^{-3}) southern pine samples re-dried at 115.5 °C compared to samples dried at 87.8 °C. They also found that hardness was not affected by CCA treatment and re-drying, but Work to Proportional Limit (WPL) and MOR were significantly reduced. No difference in the reduction of MOR was observed at re-drying temperatures of 87.8 °C and 115.5 °C. Barnes (1985) found that the effect of increasing (steam) temperature on the MOR and WPL of treated timber was highly significant, but the effect of CCA retention was significant only at the highest retention of 24.03 kg m^{-3}.

Generally, CCA treatment up to a retention of 16.0 kg m^{-3}, and re-drying up to a temperature of 60 °C, has a negligible effect on the mechanical properties of small clear-wood southern pine specimens. At higher treatment retentions (24 - 40 kg m^{-3}), MOR, WML and toughness are reduced irrespective of whether wood is air or kiln dried after treatment. The effect of CCA treatment and high temperature re-drying (i.e., > 100 °C) on wood strength is not known. Previous findings suggest that CCA treatment and re-drying has a negligible effect on MOE, the stress-strain relationship below the elastic limit, and on the hardness of small clear-wood specimens. CCA treatment and re-drying reduced WML, WPL, MOR and toughness of small clear-wood specimens although it should not be assumed that these results can be used to estimate the effects of treatment and re-drying on full-sized structural timber.

2.5.2.2. Structural size timber

The effects of CCA treatment and re-drying on the strength properties of structural size timber have mainly used southern pine (No.1 and/or No.2 grades). The maximum CCA retention level used have been 9.6 kg m^{-3}. These studies (Barnes and Mitchell, 1984; Lee, 1985; Barnes and Moore, 1987; Winandy and Boone, 1988; Winandy, 1989) have revealed that the MOE of structural size timber is not adversely affected by CCA treatment and re-drying using drying temperatures up to 115.5 °C. Table 2.3 summarizes these findings.

In some cases MOE was increased by treatment and re-drying. For example, Barnes and Moore (1987) reported that after HTD of CCA-treated (R = 4.0 kg m^{-3}) southern pine there was a statistically significant increase (2.3%) in MOE. Barnes and Mitchell (1984) also found a 6.0% increase in the Fiber Stress at the Proportional Limit (FSPL) of CCA-treated southern pine timber after HTD, but MOR was significantly reduced by about 10%.

Winandy and Boone (1988) found reductions in the MOR of southern pine structural size timber of 7 to 14% at or above the 10th to 40th percentile of the MOR property distribution after treatment and re-drying. Winandy (1989) also found a reduction of up to 13% in the MOR of CCA treated (R = 9.6 kg m^{-3}) southern pine timber after air-drying, and a reduction of 23% after kiln drying at 115.5 °C. In contrast, Winandy and Boone (1988) found no significant reduction of MOR in the extreme lower portion (below the 10th percentile) of the property distribution in air-dried southern pine timber treated to a CCA retention of 9.6 kg m^{-3}. However, WML was significantly reduced (up to 41%) by CCA treatment and re-drying

Table 2.3. A summary of studies undertaken to evaluate the effect of CCA treatment and re-drying on strength properties of structural size timber

Author	Species (Chemical)	C C A retention (kg m^{-3})	Re-drying temp. (°C)	Strength loss (%)* MOE	MOR	WML	WPL	FSPL
Barnes and Mitchell (1984)	Southern pine (CCA-A)	4.8	87.8	N S	8.3		N S	N S
		4.8	115.5	N S	11.6		N S	+6.0
Barnes and Moore (1987)	Southern pine (CCA-C)	4.0	71.1	N S				
		4.0	93.3	N S				
		4.0	121.1	+2.3				
Lee (1985)	Southern pine (CCA-C)	9.6	Air	N S	N S			
Winandy and Boone (1988)	Southern pine (CCA-C)	6.4	71.1	N S	7 - 17	6 - 29		
		6.4	115.5	N S	5 - 17	9 - 24		
		9.6	Air	N S	N S	6 - 10		
		9.6	71.1	N S	2 - 13	9 - 20		
		9.6	87.8	N S	4 - 13	8 - 30		
		9.6	115.5	N S	8 - 23	17 - 41		
Winandy (1989)	Southern pine (CCA-C)	6.4	Air	N S	N S	N S		
		6.4	115.5	N S	10 - 30	27 - 50		
		9.6	Air	N S	N S	N S		
		9.6	115.5	N S	15 - 23	34 - 46		

N S Not significant; + Significant increase

*Care should be taken when comparing strength loss figures since treatment and drying conditions vary greatly between studies.

Note: Winandy and Boone (1988) and Winandy (1989) found no significant effects of CCA treatment and re-drying on MOE, MOR and WML below the 10th percentile of the property distribution. Hence, data above are values at or above the 10th and 40th percentile for all grades of timber tested.

[Winandy and Boone, 1988], but WPL was not affected [Barnes and Mitchell, 1984].

It appears that MOE is not significantly affected by CCA treatment up to a retention of 9.6 kg m^{-3} and re-drying up to 115.5 °C, whereas, MOR and WML are significantly reduced. Strength losses are generally greater at higher retention levels and higher re-drying temperatures. The highest treatment retention examined for structural size timber is 9.6 kg m^{-3}. The variations in the magnitude of strength losses in the different studies may be attributed to the different combinations of preservative retention and re-drying temperature used, different CCA types and the inherent variability of the defect-containing timber specimens.

2.6 Summary

The literature suggests that re-drying of wood after treatment with waterborne CCA-type preservatives, may reduce wood strength properties, depending upon the drying temperature used, the retention of preservative, the type of CCA formulation, and the wood species. Most of the studies have used southern pine species (longleaf and slash pines). Limited studies have been done on radiata pine. Results for tests conducted on small clear-wood specimens and on structural size timbers do not appear to correlate well in terms of absolute values or the magnitude of strength loss for the same property [Barnes, 1986]. Previous studies imply that care needs to be taken in the CCA treatment and re-drying of wood to avoid significant reductions in strength. However, no specific treatment and re-drying schedules for any species have been established. Barnes (1986) has suggested a re-drying temperature of 71°C (160 °F), while Winandy (1988) suggested 87.8 °C (190 °F) as the upper limits for re-drying CCA treated timber. Further data are needed particularly for radiata pine.

Chapter Three

GENERAL EXPERIMENTAL METHODS

This chapter describes the main techniques and procedures used in the experiments that were carried out in this study. Specific experimental methods are described in the relevant chapters.

3.1 Materials

3.1.1. Wood/timber samples

Radiata pine is widely used as a structural timber in countries where extensive plantations of the species are available, such as in Australia, Chile, New Zealand and South Africa. The timber has sufficient strength to meet the engineering requirements for light-frame structures, weatherboards, floorings/deckings, shelving and a variety of other uses. The wood is even-textured, of medium density, is relatively easy to saw, dry, machine, nail, glue, stain, finish, and treat with preservatives [Kininmonth and Whitehouse, 1991]. Radiata pine is comparable in strength (S6, SD6) and durability (Class 4) to other widely used softwood timbers, such as Caribbean pine, loblolly pine (*Pinus taeda* L.), Maritime pine (*Pinus pinaster* Ait.) and Slash pine [Bootle, 1983].

The samples used to examine the effect of treatment and re-drying on the strength of structural timber were obtained from the Colonial Sugar Refining Co.(CSR) Softwoods at Tumut, NSW. This timber had the following specifications.

Species: Radiata pine (*Pinus radiata* D. Don)

Dimensions: Nominally 45 x 90 x 2400 mm (672 pieces)

Section type: Dressed (mixed) flat-sawn and quarter-sawn having sapwood and/or heart-in-material

Seasoning (prior to treatment): Kiln dried to approximately 12% MC at 120 °C DBT and 90°C WBT for 18 - 24 h

Grade: Machine stress graded in accord with AS 1748-1978 to F5

Note: The stress rating assumes the presence of the maximum allowable extent of strength-reducing characteristics (AS 2858-1986). For example, for stress grade F5 (also structural grade No. 5): Knots on the face of the timber, wholly within the central 80% of the face width and knot-area-ratio (KAR) not exceeding 60% can be permitted. Knots on edge not exceeding 66% KAR are permissible. Surface checks, individually not exceeding 600 mm in length nor 2.0 mm in width are permissible.

3.1.2. CCA preservative

There are a number of different CCA preservative formulations commercially available (Appendix C). For this study, a CCA -Type C formulation (Tanalith C salt based solution) was used since it is the most commonly used preservative for treating radiata pine. The chemical solution concentrate which was supplied by Koppers Australia had the following specification (AS 1604-1980):

Active elements	Compound	Percent composition
Copper	Copper Sulphate ($CuSO_4 \times 5H_2O$)	35.0
Chromium	Potassium dichromate ($K_2Cr_2O_7$)	45.0
Arsenic	Arsenic pentoxide ($As_2O_5 \times 2H_2O$)	20.0

3.2. Preparation of specimens

3.2.1. Small clear-wood specimens

A number of pieces of timber measuring 45 x 90 x 2400 mm were randomly picked from the timber samples above (Section 3.1.1.) and cut to produce small clear-wood specimens. Sections of timber containing knots, grain irregularities and other growth defects were not selected. The timber was sawn into 30 mm square cross section sticks. These sticks were then dressed in a planer to produce 25 mm square cross-sections and cut to lengths of 450 or 100 mm to produce bending and compression test specimens, respectively. The dimensions and weight of each specimen were obtained using a vernier caliper and an electronic balance. These measurements were used to determine the air density of each specimen. Density (D) was taken as the ratio of the air dry mass of the specimen to its air dry volume. Strength properties are known to be directly related to density and specimens having the same, or equivalent density were matched, hence, the specimens were said to be D-matched. D-matching was employed to minimize the random differences between experimental groups for experiments involving small clear-wood specimens. D-matched specimens were labelled for identification and kept in a conditioning room at 20 ± 1°C and 65 ± 5% relative humidity (RH) to equilibrate to 12% EMC (equilibrium moisture content) until ready for testing.

3.2.2. **Structural size timber**

The specifications of the structural size timber samples are described in Section 3.1.1. Each timber sample was subjected to two pre-selected loads below the elastic limit of the timber, such as P1 and P2, in a static bending test as illustrated in Figure 3.1. The corresponding deflections, d1 and d2 were measured and noted. The E value (i.e. modulus of elasticity) was then calculated using these measurements as follows;

$$E = \frac{\Delta P}{\Delta d} \times \frac{L^3}{4bh^3}$$

Where: E = modulus of elasticity (MPa)
ΔP = difference between the loads [P2 - P1] in (N)
Δd = difference between the deflections [d2 - d1] (mm)
L = span of beam (mm)
b = breadth of beam (mm)
h = depth of beam (mm)

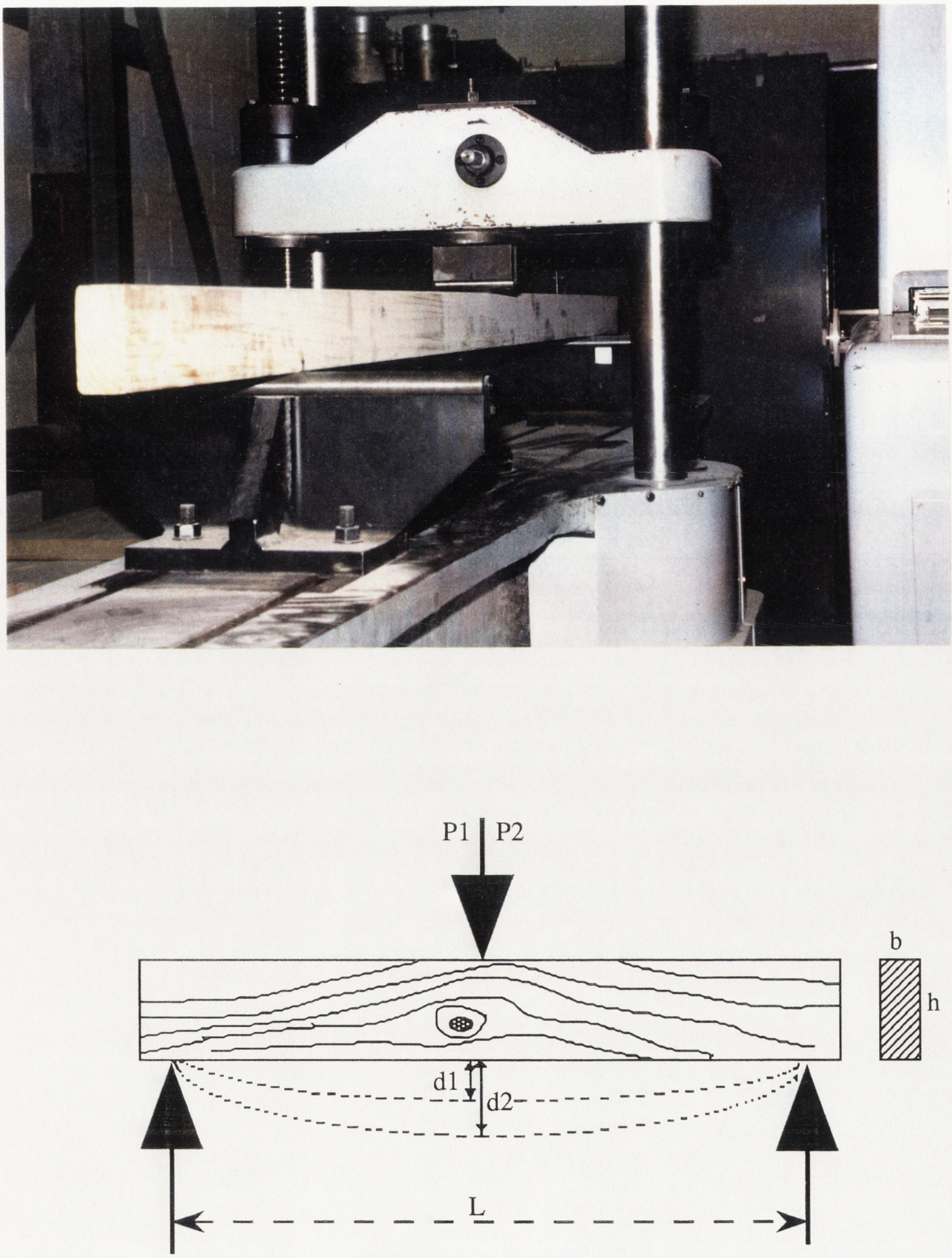


Figure 3.1 Loading configuration for E-matching of structural size timber

Samples having identical E value were used as matched samples, hence, the samples were said to be E-matched. This technique was used to minimized the random differences between the experimental groups for experiments involving structural sized timber specimens. E-matched specimens were labelled for identification and box-piled under cover in the timber-testing laboratory of ANU Department of Forestry until ready for testing.

3.3. CCA treatment

Specimens were pressure treated with CCA in a pilot scale preservation plant (Plate 1). A full-cell treatment process was used to treat the timber since most previous studies have also used this process (Winandy, *et al.*, 1983; Bendtsen, *et al.*, 1983; Barnes and Mitchell, 1984; Lee, 1985) and the full-cell treatment process is commonly used to treat radiata pine with CCA preservative. Each treatment cycle consisted of an initial vacuum of -90 kPa held for 30 minutes. The pressure cylinder was then flooded with preservative. Pressure of 1400 kPa was applied for 2 hours and then a final vacuum of -90 kPa was applied for 15-20 minutes.

3.4. Drying of specimens

Specimens were either air dried under cover, dried in a laboratory oven or dried in a pilot scale kiln (Plate 2). The specific drying procedures used are described in Chapters 4, 5 and 6.

3.5. Conditioning of specimens

After treatment, treated (CCA and water) specimens and untreated controls were box piled using 6-mm thick stickers and placed in a conditioning room at 20 ± 1°C and 65 ± 5% relative humidity (RH). The specimens remained in the conditioning room until they attained a constant weight. This usually took four to six weeks.

Plate 1. The pilot scale timber preservation plant used for pressure treatment of wood

Plate 2. The pilot scale kiln used for the drying of timber specimens

Conditioning of structural size timber was done under cover. Treated timber samples were boxed-piled using 25-mm thick stickers for several months until their MC reached that of the controls (i.e., the untreated original stock). The MC of the water treated timber samples was measured periodically using an electric moisture meter and the moisture content of CCA treated timber was monitored by weighing and oven drying selected samples. Occasionally the timber pile was re-arranged to allow even drying of specimens.

3.6 Strength testing

Strength testing of both clear wood and structural timber specimens was carried out at the ANU timber testing laboratory under normal room conditions (~20°C and 58% RH). Static bending and compression parallel to the grain tests were done using a Shimadzu universal testing machine (Plate 3).

3.6.1. Static bending

For small clear-wood specimens, bending tests were carried out with central-point loading as shown in Figure 3.2. The rate of loading was 2.5 mm per minute applied to the radial face of each specimen until it failed. After each test, small blocks (~25 to 30 mm in length) were cut adjacent to the broken portion of the specimen for MC determination and to determine the preservative retention of the specimen.

For the structural size timber, a two-point loading system was used. The configuration of this loading system is shown in Figure 3.3. A loading rate of 3.0 mm per minute was applied to the edge (breadth) of the timber until it failed. After each test, wood blocks (~ 10 to 15 mm thick) were cut adjacent to the broken portion of the specimen. These blocks were used to determine the MC and preservative retention of the specimens.

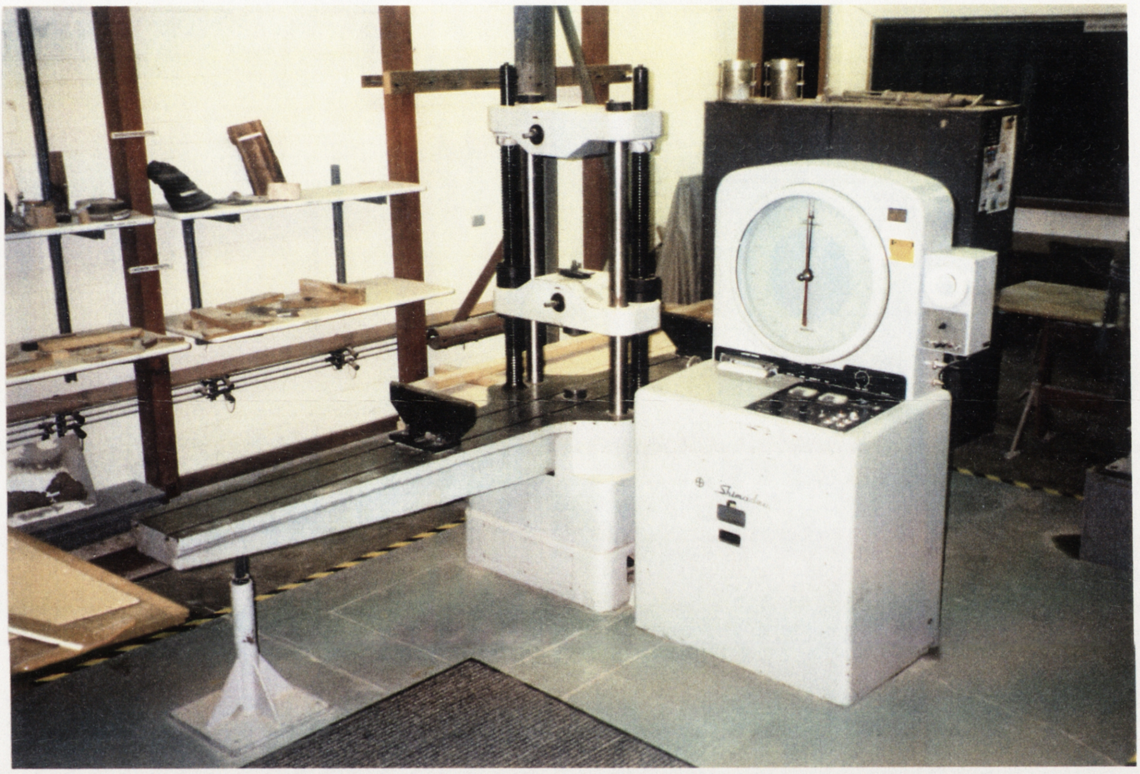
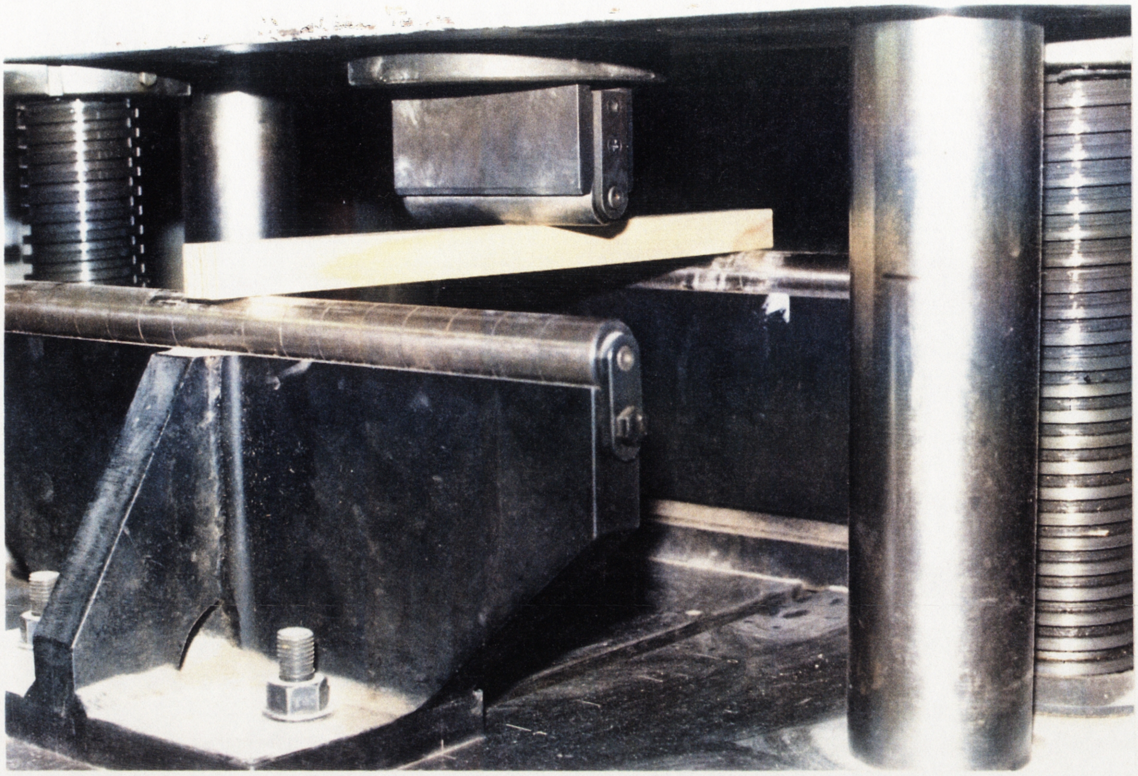


Plate 3. The Shimadzu universal testing machine used for strength testing of small clear-wood specimens and structural size timber



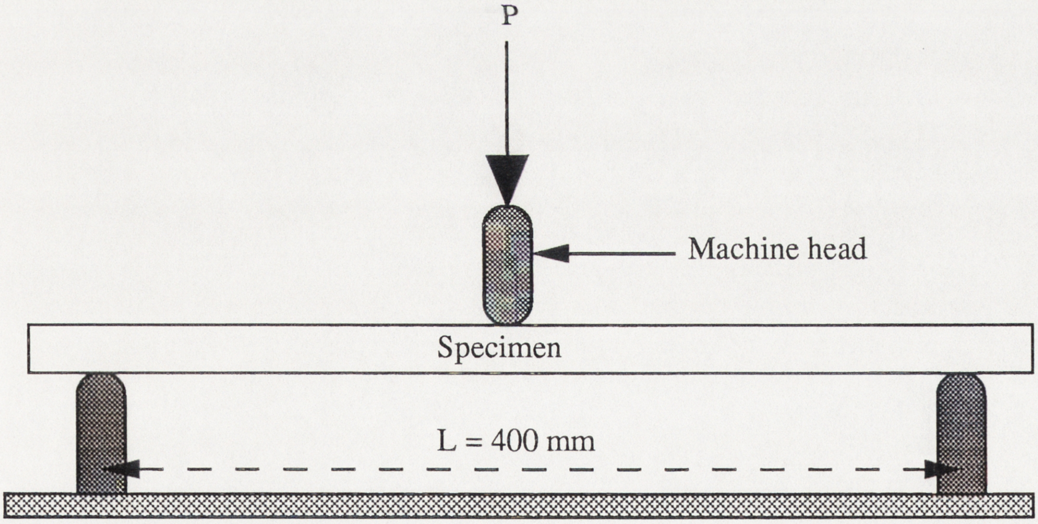
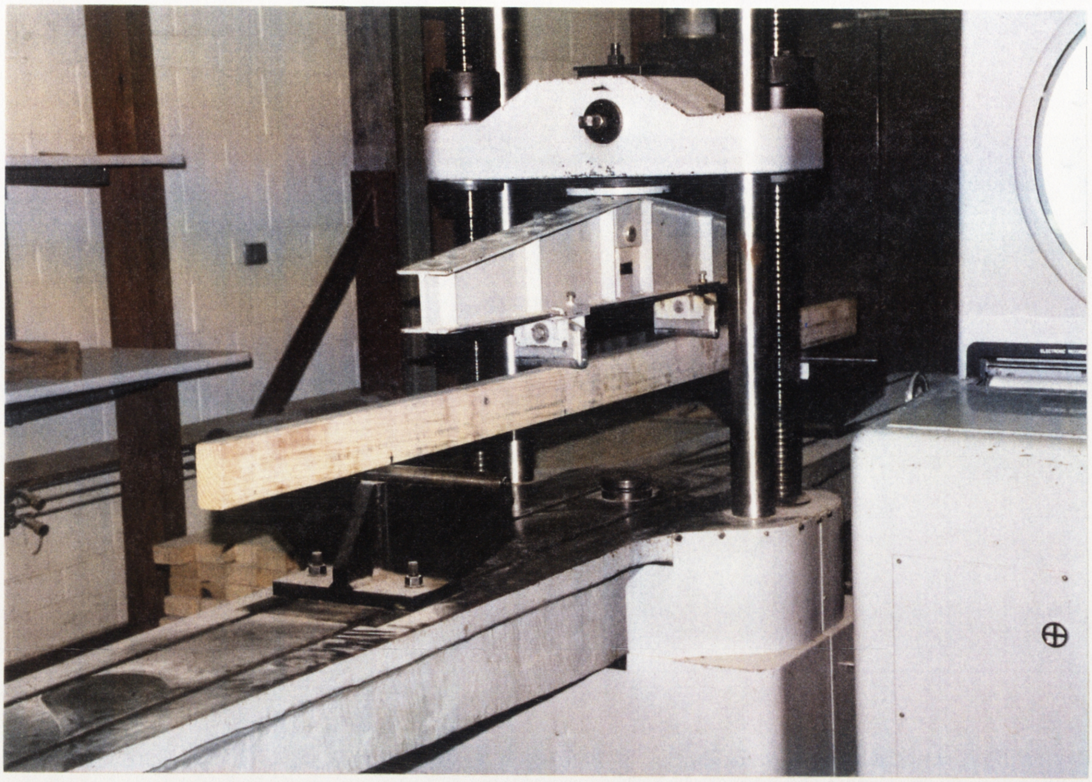


Figure 3.2 Loading configuration for the static bending test for small clear-wood specimens



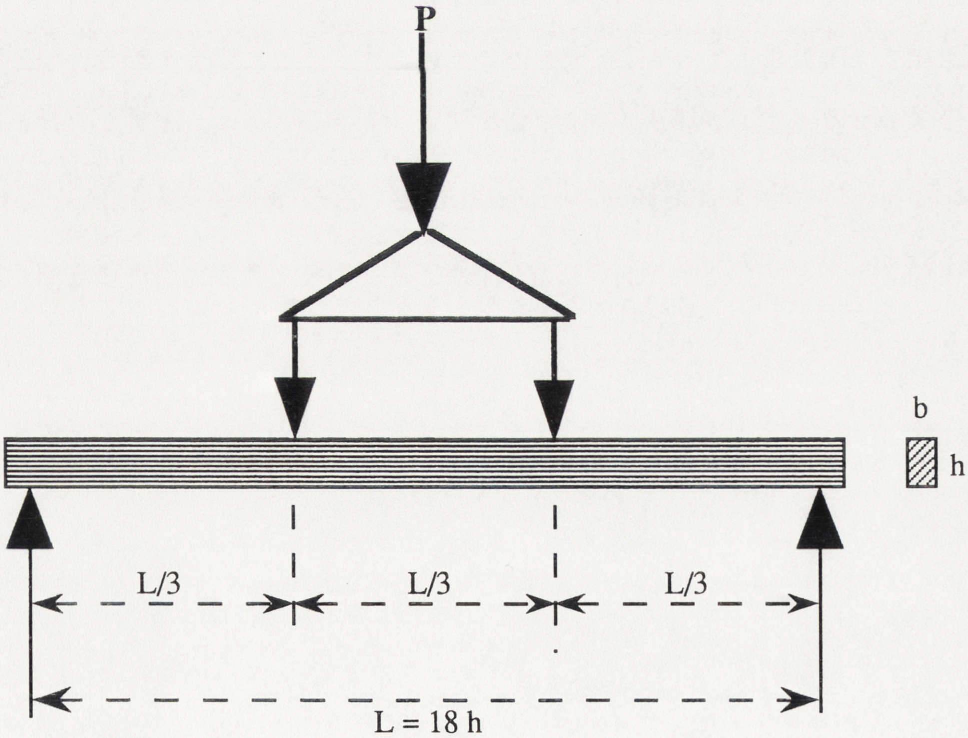


Figure 3.3 Loading configuration for bending test of structural size timber

3.6.2. Compression parallel to the grain

Tests of compression parallel to the grain were carried out using the loading configuration shown in Figure 3.4. A rate of loading of 2.0 mm per minute was applied to the end of the specimen until it failed. This test was only conducted on small clear-wood specimens.

3.7. Property determinations and calculation of strength parameters

3.7.1. Wood moisture content

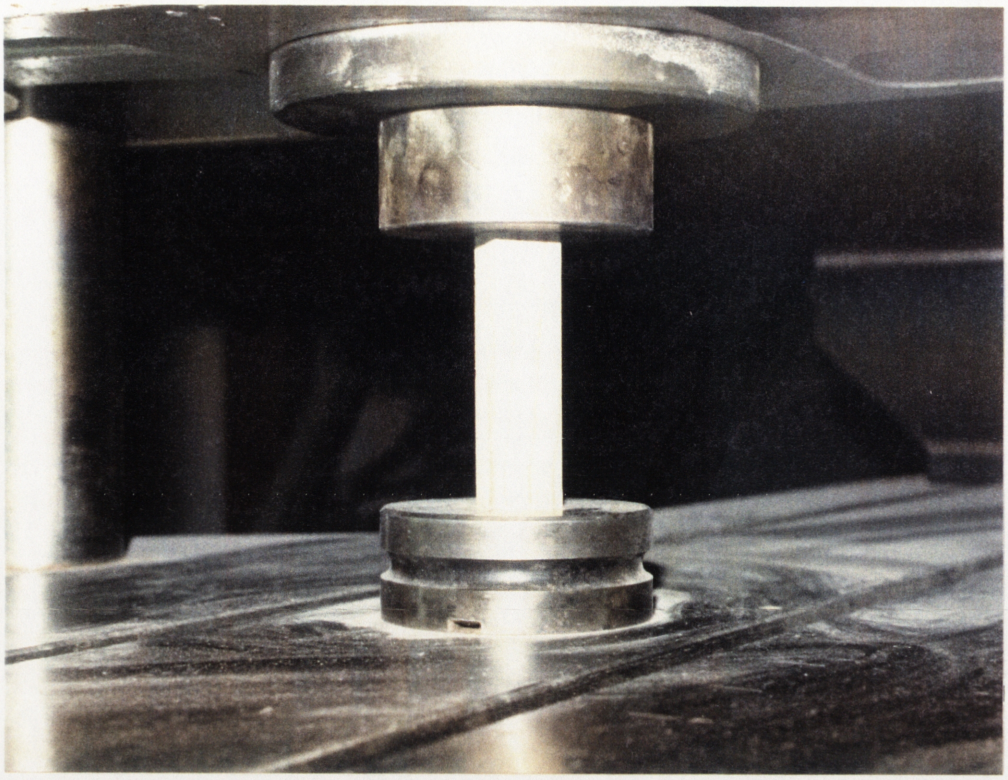
Wood blocks that were taken adjacent to the broken portion of each specimen were weighed and oven-dried at 105 ± 5 °C until they attained a constant weight. MC was calculated as follows;

$$MC = \frac{Wi - Wo}{Wo} \times 100$$

Where: MC = moisture content (%)
Wi = initial weight of sample (g)
Wo = oven-dry weight of sample (g)

3.7.2. Preservative retention

The CCA retention of samples were determined using an Asoma X-ray (Model LCA-XRF) fluorescence analyzer (Plate 4). Wood samples were cut adjacent to the broken portion of tested specimens and ground in a Wiley mill (Plate 5) to pass a 30 mesh sieve. Ground samples were then compressed in a hand compactor (Plate 6) to form briquets that fitted the sample holder of the X-ray instrument. The CCA retention of the compacted samples were then analyzed. For each sample, retention (in kg m^{-3}) of copper sulphate, potassium dichromate and arsenic pentoxide is given in the machine print-out. The CCA retention of the specimen was then calculated as the sum of retentions of each constituent.



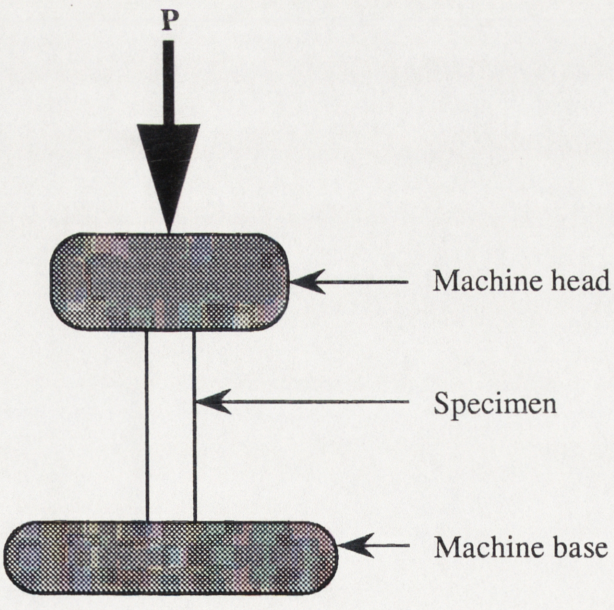


Figure 3.4 Loading configuration for the compression parallel to the grain test

Plate 4. The Asoma X-ray fluorescence analyzer (Model LCA-XRF) used to determine the preservative retention of treated specimens

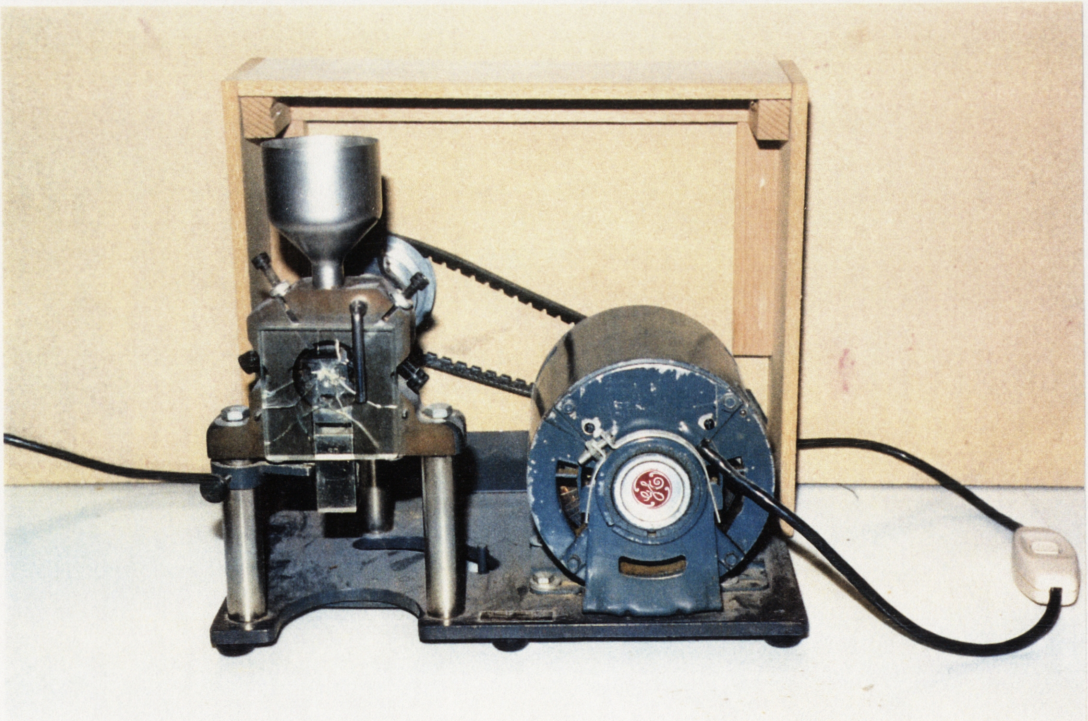


Plate 5. The Wiley mill used to grind wood samples to wood flour

3.7.3. **Modulus of rupture (MOR)**

For small clear-wood specimens, MOR was calculated using the common flexure equation for a beam loaded with a concentrated load at the center of the span as follows:

$$MOR = \frac{1.5\ PL}{bh^2} \qquad \text{[Haygreen and Bowyer, 1982]}$$

For structural size timber, where a two-point loading system was used, MOR was calculated using the following formula;

$$MOR = \frac{3\ P\ a}{bh^2} \qquad \text{[ASTM D 198; AS 1749-1978]}$$

Where: MOR = modulus of rupture (MPa)

P = the breaking (maximum) load (N)

L = beam span or distance between supports (mm)

a = distance between supports and nearest load point (mm)

b = breadth of the specimen (mm)

h = depth of the specimen (mm)

3.7.4. **Modulus of elasticity (MOE)**

For small clear-wood specimens, MOE was calculated using the following formula;

$$MOE = \frac{Pp\ L^3}{48\ I\ D} \qquad \text{[Haygreen and Bowyer, 1982]}$$

Where: MOE = modulus of elasticity (MPa)

Pp = load on beam at proportional limit

D = deflection of beam at neutral axis between reaction and center of beam at the proportional limit (mm)

I = moment of inertia, $= \frac{bh^3}{12}$ (mm^4)

The other variables are as defined in Section 3.7.3.

For structural size timber specimens, MOE was calculated as

$$\mathrm{MOE} = \frac{\mathrm{Pp\ a}}{4\ \mathrm{bh^3\ D}} \times (3L^2 - 4\ a^2) \qquad \text{[ASTM D 198]}$$

The loads at proportional limit (Pp) for each specimen were determined from the plot of load versus deflection traced by the electronic chart recorder (Plate 7) of the Shimadzu universal testing machine. Pp corresponds to the point of deviation from the straight line portion of the plot. Figure 3.5 presents an idealized illustration of Pp.

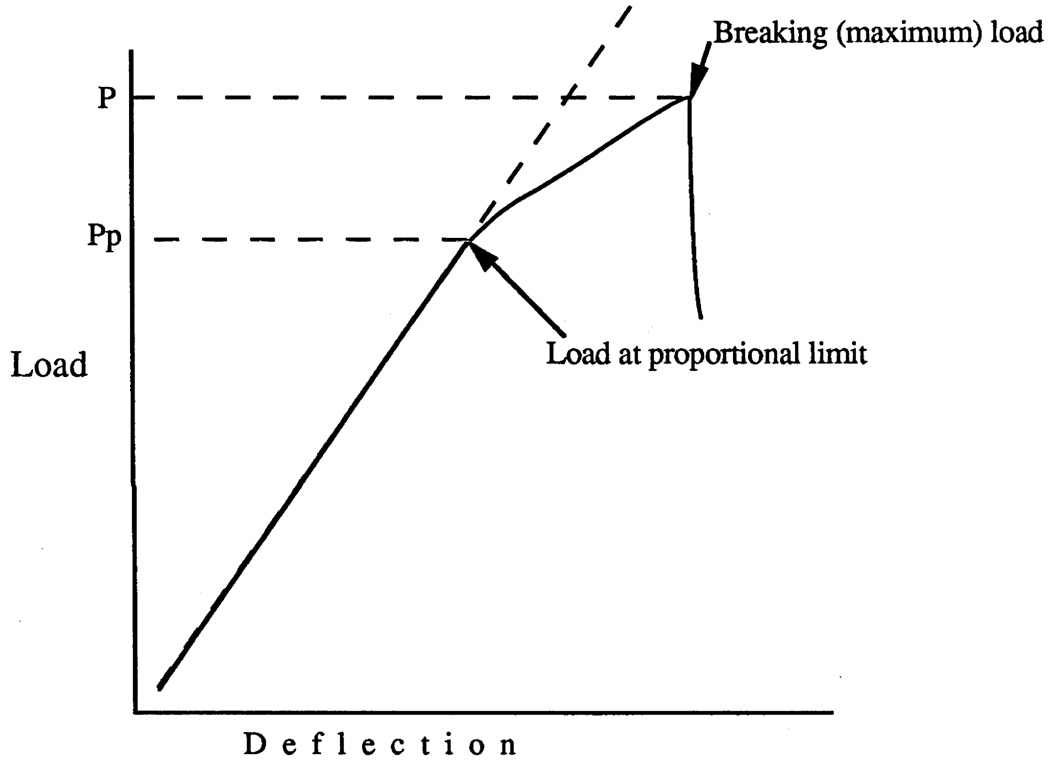


Figure 3.5 Idealized plot of load versus deflection showing the load at proportional limit (Pp)

3.7.5. Maximum crushing strength (MCS)

MCS was calculated as

$$\mathrm{MCS} = \frac{P}{A} \qquad \text{[Haygreen and Bowyer, 1982]}$$

Where: MCS = maximum crushing strength (MPa)
P = maximum load (N)
A = area of cross-section of the specimen (mm^2)

Plate 6. The hand press compactor used to form plugs of wood from treated wood flour

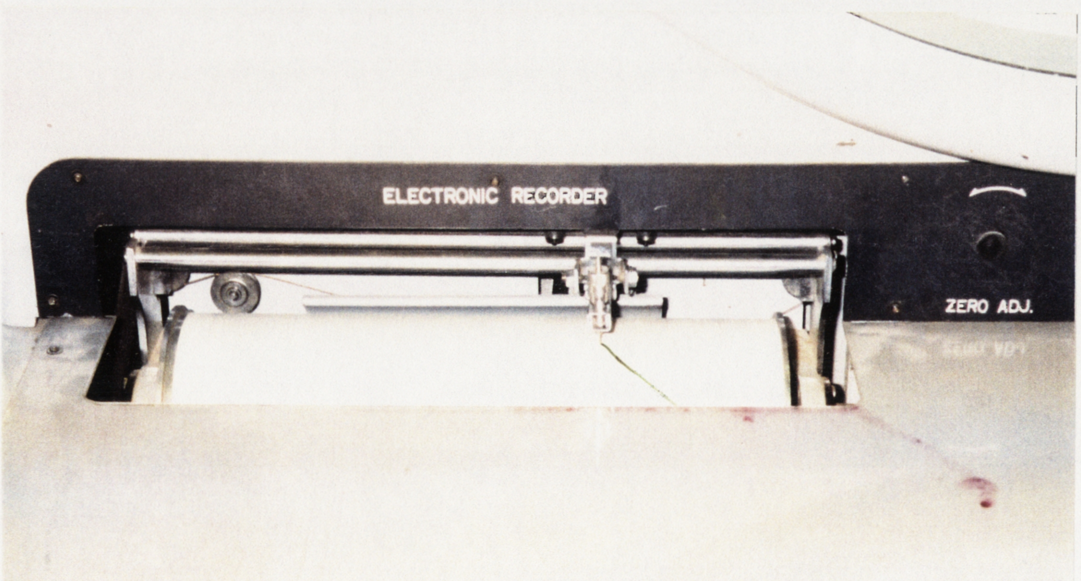


Plate 7. The electronic chart recorder of the Shimadzu universal testing machine

3.8 Sample size estimation

Preliminary experiments on small clear-wood specimens revealed that the strength data (e.g., MOR) for radiata pine was normally distributed with an average coefficient of variation (CV) of 15.35%. On that basis, and using a 95% confidence level an estimate of the minimum sample size needed for the experiments was calculated as follows;

$$n = (t/0.05 \times CV)^2 \qquad \text{[ASTM D 2915-74]}$$

Where:
- n = sample size
- t = t-statistic (~ 2 for this purpose)
- 0.05 = precision of estimate (i.e., at 95% level)
- CV = coefficient of variation

Thus, the minimum sample size for experiments using small clear-wood specimens was ($n = [2/0.05 \times 0.1535]^2 = 37.7$) 38 pieces. For structural size timber, a coefficient of variation of 18% for the MOR of radiata pine has been reported for 50 x 50 mm cross-section specimens [Kininmonth and Whitehouse, 1991]**. Using this value for the 95% confidence sampling, the minimum sample size was ($n = [2/0.05 \times 0.18]^2 = 51.84$) 52 pieces. The number of samples used in the experiments reported subsequently are greater than the minimum numbers calculated above.

3.9 Data analysis

Data gathered from each experiment were treated as a data set. Data sets were analysed by Genstat* (Genstat 5 Release 2.2, Lawes Agricultural Trust) for diagnostic checking of residuals and homoscedasticity. Units (or values) that were

---

* One of a number of computer software package used for statistical analysis of data with the Sun/Unix computer.

** (see overleaf)

shown to have large residuals were discarded from the set in subsequent analyses of variance (ANOVA) and paired t-tests [Snedecor & Cochran, 1967]. Statistical analyses were performed using Statview.** When ANOVA revealed significant ($p < 0.05$) differences between treatments, a paired t-test was carried out to test the significance of differences between treatments. T-values with corresponding probability values are presented to indicate the significance of the tests (e.g., significant for $p < 0.05$ and not significant for $p > 0.05$). ANOVA tables, tables of means, standard deviations, standard errors and comparisons of means are presented in Appendix D.

**The coefficient of variation for structural radiata pine (90mm x 35mm F5 MSG) has recently been found to be 44%. This information was published in an internal CSIRO report (Leicester et al. 1988. Structural Engineering Properties of Machine Stress Graded Australian Grown Radiata Pine. CSIRO-DBCE Technical Report TR88/1) and was not available to me during the planning of this thesis-indeed I only learned of its existence as a result of the examination of this thesis. The use of a coefficient of variation for structural radiata pine of 44% rather than 18% greatly increases sample sizes, i.e., $n = [2/0.05 \times 0.44]^2 = 309.76$ and it is recommended for future work that this is taken into account.

** A computer software package used for statistical analysis of data with the Macintosh (Apple) computer.

Chapter Four

PRELIMINARY STUDIES USING SMALL CLEAR-WOOD SPECIMENS

This chapter examines the effects of CCA treatment and air drying, water treatment and air drying and heat (oven drying) on the MOE, MOR and MCS of small clear-wood radiata pine specimens. For each treatment, a separate experiment was conducted to examine a specific hypothesis related to the main aim of the thesis. These experiments are considered preliminary in the sense that they were carried out to enable the selection of appropriate treatments for subsequent experiments. However, the results in this chapter can be used to support the aim of this thesis.

4.1 Effect of CCA treatment and air drying

4.1.1 Introduction

CCA is acidic (pH = 1.6 - 3.2) and therefore has the potential to reduce the strength properties of wood [Winandy, *et al.*, 1983]. To examine this, a preliminary experiment on the effect of CCA treatment and air drying on MOR and MCS of small clear-wood specimens was carried out. The aim of the experiment was to determine whether treatment with CCA preservative and subsequent air drying affects the MOR and MCS of small clear-wood radiata pine specimens. MOR and MCS were selected for the evaluation of treatment effects because they are the measures of maximum strength of wood as a beam and column, respectively. Also, MOR has often been shown in the literature to be deleteriously affected by CCA treatment.

4.1.2 Experimental procedure

Samples were cut from thirteen pieces of radiata pine approximately 50 x 150 mm in cross-section and of assorted lengths, from 4.0 to 5.0 m. The timber was purchased in a rough green condition from a local sawmill in the ACT. The timber was forced air-dried inside a kiln (Plate 2) using only the fans. The MC of the timber was periodically checked using a resistance type direct current electric moisture meter. When the MC of the timber reached an average of 18 ± 5% the timber was removed from the kiln and allowed to cool for 24 h. Small clear-wood specimens were then prepared as described in Section 3.2.1.

4.1.2.1 **Experimental design**

Two types of strength tests were conducted - a bending test to determine the effect of CCA treatment and air drying on MOR and a compression test to determine the effect of treatment and air drying on compression parallel to the grain (MCS). For each strength test, two paired experiments, designed to compare specimens having nearly equivalent density values (D-matched), were undertaken. One experiment examined the effect of CCA treatment and air drying at a high treatment retention (A) and the other examined the effect of CCA treatment and air drying at a lower retention (B). Forty D-matched specimens were randomly assigned to Experiment-A and thirty D-matched specimens were assigned at random to Experiment-B. For each matched pair, one piece was randomly allocated for CCA treatment and air drying and the other piece served as a control. Figure 4.1 illustrates the design of the experiments.

4.1.2.2 **CCA treatment**

Two separate treatments were carried out. One for a target retention of 40.0 kg m^{-3} (high treatment retention) and the other for a target retention of 12.0 kg m^{-3} (low treatment retention). Solution concentrations of 6.23% (pH ~ 1.83) and 2.10% (pH ~ 2.16), respectively, were used to treat the timber to the desired retention levels. The treatment procedure was described in Section 3.3. Specimens were weighed before and after treatment. Retention of preservative was calculated using the weight gained after treatment according to the following formula:

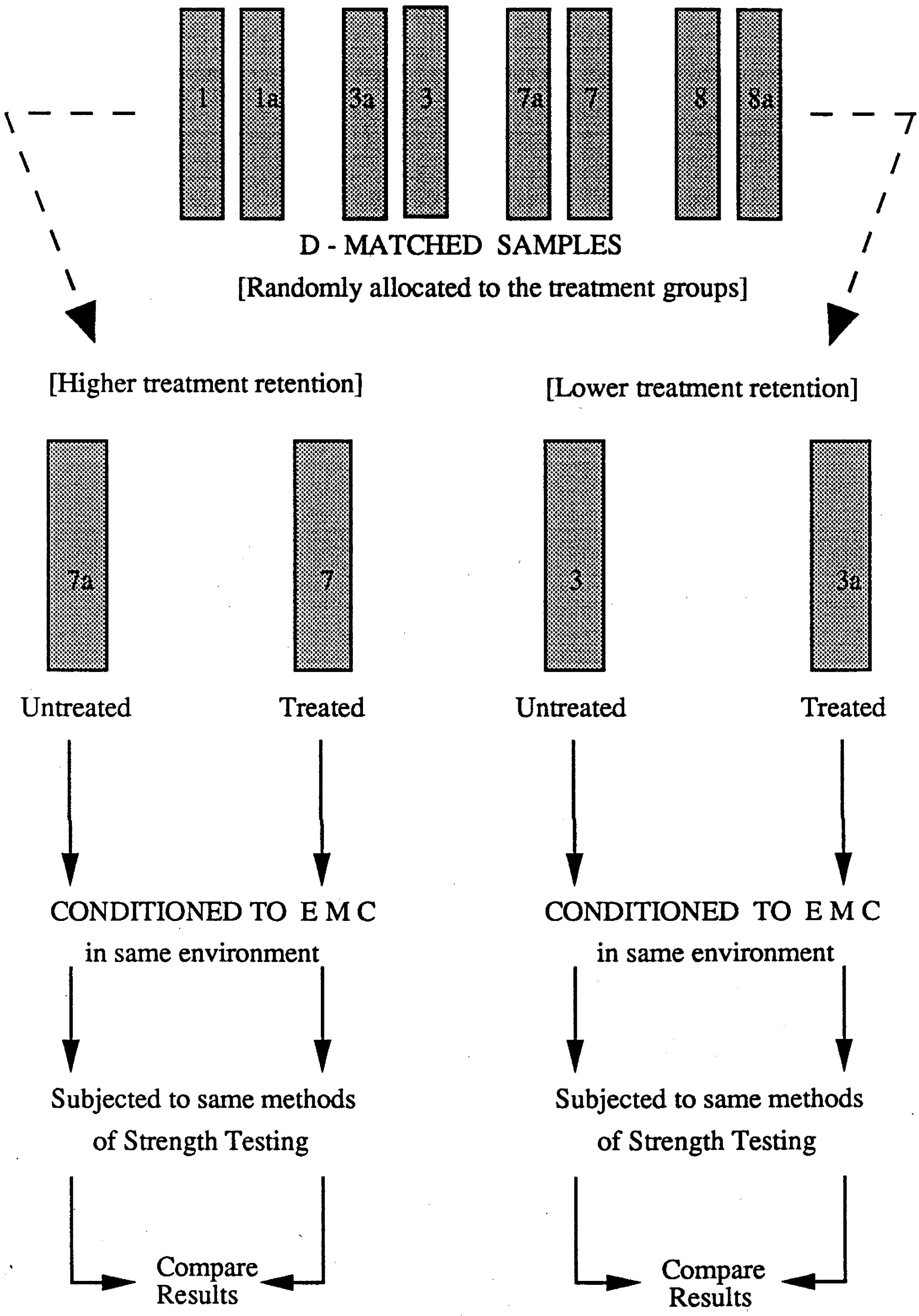


Figure 4.1. The design of the experiments to determine the effect of CCA treatment and air drying on the strength (i.e., either bending or compression parallel to the grain) of small clear-wood specimens

$$R = 10^6 \times C \times \frac{(Wt - Wu) \times \frac{1}{SG}}{l \times w \times d}$$

Where: R = retention (kg m^{-3})
C = solution concentration (in decimal)
Wt = weight of treated specimens (g)
Wu = weight of untreated specimens (g)
l, w, d = length, width, and depth of specimen (mm)
SG = specific gravity of the solution
10^6 = unit conversion factor

4.1.2.3 Air drying, conditioning and strength testing

Treated specimens were box-piled under cover using 6 mm thick stickers for 32 days to allow the samples to air dry and to allow CCA fixation to occur. The specimens were then conditioned as described in Section 3.5. Bending and compression tests were done as described in Sections 3.6.1 and 3.6.2, respectively.

4.1.2.4 Statistical analyses

Strength data were analyzed without adjusting values to account for differences in EMC due to treatment. Winandy, *et al.*, (1985) stated that adjusting data for increases in EMC may, in part, mask the effect of CCA treatment on wood strength, since increases in EMC are one of the effects of CCA treatment.

Exploratory data analysis revealed no extreme data points. Diagnostic checks of residuals using Genstat (Section 3.9) confirmed that the assumptions under a standard paired t-test intended for this experiment were not violated. Tests of significance of the differences of treatment means were carried out by comparing the calculated t-value for the treatment against the t-value (2-tail) at the 95% level of significance [Snedecor and Cochran, 1967].

4.1.3 **Results and discussion**

The average EMCs of the untreated (control) specimens which were kept in the same environment as the treated specimens (i.e., inside the conditioning room) were 11.6 - 11.9% for the bending test specimens and 11.2 - 11.6% for the compression test specimens. The EMCs of the CCA-treated and air dried bending and compression test specimens were 14.9 - 15.6% and 14.3 - 15.6%, respectively. Higher EMCs for CCA-treated specimens compared to untreated specimens were also noted by Bendtsen, *et al.*, (1983) and Winandy, *et al.*, (1985). Results here support previous observations that CCA treatment increases the EMC of wood.

Tables 4.1a and 4.1b summarize the results of the experiments to determine the effect of CCA treatment and air drying on MOR and MCS, respectively.

4.1.3.1 **Modulus of rupture (MOR)**

The effect of CCA treatment and air drying on MOR was different for the two retention levels. At the higher CCA retention, MOR increased by 9.20 MPa or 15.0%, while at the lower retention level MOR decreased by 2.66 MPa or 3.4% compared to the untreated controls. Statistical analyses show that the increase in MOR of 15.0% at the higher treatment retention level was highly significant ($p < 0.01$). At the lower treatment retention the loss in MOR was statistically insignificant ($p > 0.05$). Bendtsen, *et al.*, (1983) and Winandy, *et al.*, (1985) also found insignificant effects of CCA treatment on the MOR of small clear-wood southern pine specimens at low treatment retentions (i.e., < 16.0 kg m^{-3}). However, when using a CCA-A preservative at high treatment retentions (~ 40.0 kg m^{-3}) Bendtsen, *et al.*, (1983) found a 19% loss in the MOR of southern pine while Winandy, *et al.*, (1985) using a CCA-C preservative found no significant effect of treatment and air drying on the MOR of southern pine. Differences in results between studies may be due to CCA type and/or species of wood, as has been suggested by Barnes (1986) and Winandy (1988).

Table 4.1a The effect of CCA treatment and air drying on MOR of small clear-wood radiata pine specimens

Expt.	Treatment group [a]	EMC (%)	Retention (kg m^{-3})[c]	Strength MOR (MPa)[b]	Strength change (%)	Paired t-value [d]
A	Control (40)	11.6		61.4 (7.05)		
	Treated (40)	15.6	37.5 (40)	70.6 (8.75)	+15.0	- 7.99** (0.0001)
B	Control (30)	11.9		77.2 (9.09)		
	Treated (30)	14.9	13.1 (12)	74.6 (7.07)	-3.4	1.47+ (0.152)

a, b, c, d -- numbers in parenthesis refers to sample size, standard deviation, target retention, and significant probability (2-tail), respectively.

** -- highly significant

+ -- not significant

Strength increases due to CCA treatment and air drying may be due to the presence of CCA reaction products in the wood cell wall microcavities. These may provide reinforcement to the wood cell walls especially at high retentions. Particle reinforcement is a common method of improving the mechanical properties of metals [Van Vlack, 1967]. The technology is particularly effective when the introduced particles have no degradative effect on the substrate material. In this experiment where the CCA used showed little degradative effect MOR may have been enhanced by the presence of preservative salts in the wood cell walls.

4.1.3.2 **Maximum crushing strength (MCS)**

The MCS at both retention levels decreased after treatment. At the higher retention level MCS decreased by 2.42 MPa or 5.6% compared to the control. At the lower retention level, MCS decreased by 3.16 MPa or 7.0% compared to the control. Both decreases in MCS at the higher and lower treatment retentions are statistically significant ($p < 0.05$). This decrease in MCS may be due partly to the higher EMC of the treated specimens compared to the untreated control. Generally, wood strength decreases as it gains moisture within the hygroscopic range [Panshin and de Zeeuw, 1980]. However, there may be other explanations for the decreases in MCS after treatment.

Table 4.1b The effect of CCA treatment and air drying on the MCS of small clear-wood radiata pine specimens

Expt.	Treatment group [a]	EMC (%)	Retention (kg m^{-3}) [c]	Strength MCS (MPa) [b]	Strength change(%)	Paired t-value [d]
A	Control (40)	11.6		43.3 (5.52)		
	Treated (40)	15.6	35.1 (40)	40.9 (5.84)	-5.6	2.52* (0.016)
B	Control (30)	11.2		45.4 (4.65)		
	Treated (30)	14.3	12.3 (12)	42.2 (5.45)	-7.0	2.56* (0.016)

a,b,c,d -- numbers in parenthesis refers to sample size, standard deviation, target retention, and significant probability (2-tail), respectively.
* -- significant at 95% level

When wood is subjected to compression load along the grain, the cell walls tend to kink. The kink is usually initiated at points of weakness in the cell wall structure and the kink usually forms at an angle of 45° to 60° to the longitudinal axis of the specimen [see Figure 4.2]. Because of this effect the compressive strength (MCS) of wood is low [Ashby and Jones, 1986]. It is possible that CCA salt granules in the cell walls may act as a focus for stress development during compression testing and cause kinking at lower levels of stress. Kinking failure was more prevalent in CCA-treated specimens and was observed in about 20 - 30% of tested treated specimens. Others specimens showed either crushing, wedge splitting or shearing failures.

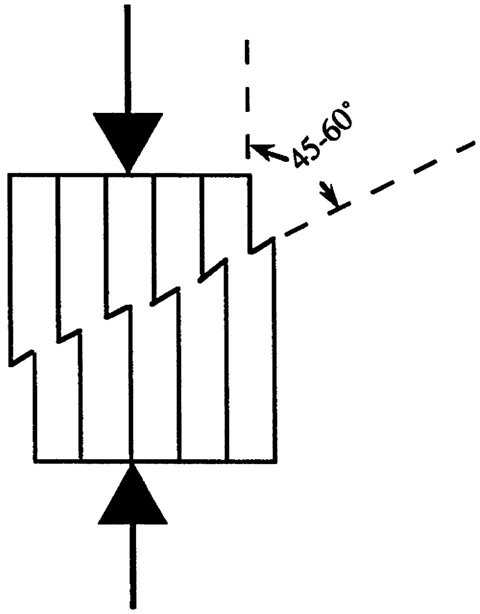


Figure 4.2 Kinking failure in compression parallel to the grain

4.1.4 Conclusion

CCA treatment and air drying has no degradative effect on the MOR of small clear-wood radiata pine specimens. However, CCA treatment and air drying did have a slight but significant ($p < 0.05$) weakening effect on the MCS of small clear radiata pine specimens.

4.2 Effect of water treatment and re-drying

4.2.1 Introduction

Strength losses in CCA-treated wood after re-drying may be due to the dissolved salts present in the aqueous CCA solution or due to the chemical and physical effects of the solvent (i.e., water). Using only water as the treating medium removes the influence of the preservative constituents (the CCA salts) and enables the effect of the solvent on the mechanical properties of wood to be examined.

The aim of this experiment is to determine the effect of water treatment and re-drying on the MOE, MOR and MCS of small clear-wood radiata pine specimens.

Subsequent chapters examine the effect of CCA treatment and re-drying on the same properties.

4.2.2 **Experimental design and procedure**

The design of this experiment is given in Figure 4.3. Two sets of specimens were prepared from the timber described in Section 4.1.2. One set was used for bending tests to evaluate the effect of water treatment and re-drying on MOE and MOR. Another set was used to evaluate the effect of water-treatment and re-drying on MCS. Each set of specimens consisted of 26 groups, with three D-matched specimens per group. Each piece within a group was randomly allocated to the three experimental treatments, i.e., water-treated and air dried; water-treated and kiln dried and untreated controls. Specimens were pressure treated with Canberra tap water in the treatment cylinder using the procedure described in Section 3.3. The untreated controls remained in the conditioning room until prior to strength testing.

4.2.2.1 **Re-drying, conditioning and strength testing**

After water treatment some specimens were boxed piled using 6 mm thick stickers and allowed to air dry under cover at ambient conditions (~22 °C, RH~ 58%). These specimens remained in place until they attained a constant weight. Some other water treated specimens were oven dried in a laboratory oven at 96.5 °C for 18 hours.

After drying, all specimens were conditioned as described in Section 3.5 prior to strength testing. Strength testing was carried out as described in Section 3.6.1 for bending and Section 3.6.2 for compression tests.

4.2.3. **Results and discussion**

The results are summarized in Table 4.2 including the results of paired t-tests. The probability value for each t-value is presented to indicate levels of significance.

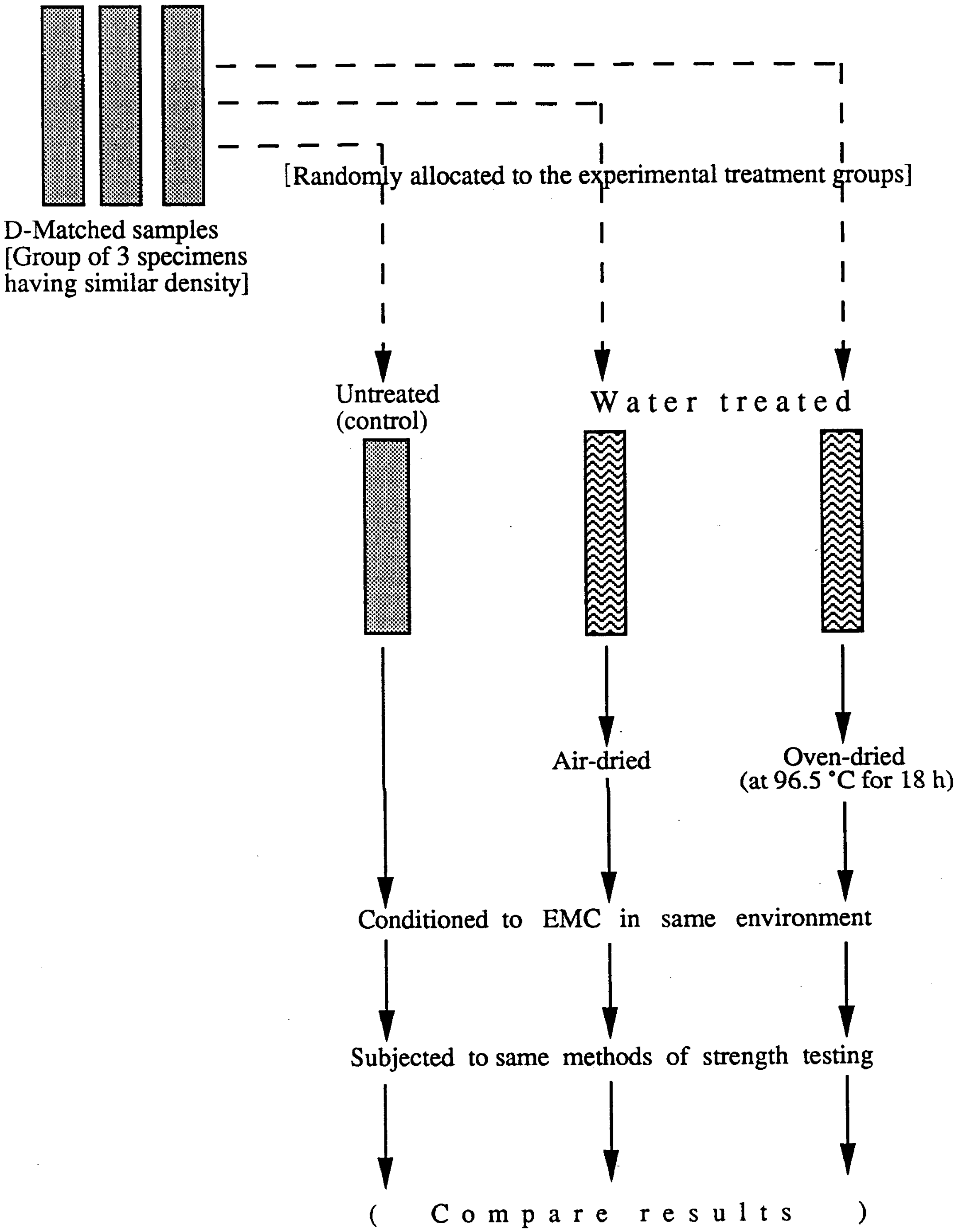


Figure 4.3 The experimental design used to evaluate the effect of water treatment and re-drying on the mechanical properties of small clear-wood specimens.

Table 4.2 **The effect of water treatment and re-drying on the MOE, MOR and MCS of small clear-wood radiata pine specimens**

Property	Treatment group [a]	EMC (%)	Property mean (MPa)[b]	Strength change (%)	Paired t-value [c] (2-tail)
MOE	Control	11.0	10298.6 (922.17)		
	Water-treated Air-dried	11.6	11017.7 (1203.49)	+7.0	-2.483 (0.020)*
	Water-treated Oven-dried	9.0	11370.5 (1204.70)	+10.4	-4.109 (0.0004)**
MOR	Control	11.0	87.0 (8.07)		
	Water-treated Air-dried	11.6	83.5 (6.93)	4.1	1.769 (0.0891)+
	Water-treated Oven-dried	9.0	86.0 (10.51)	1.2	0.446 (0.659)+
MCS	Control	10.8	49.1 (5.68)		
	Water-treated Air-dried	11.8	47.6 (3.72)	2.9	1.23 (0.2303)+
	Water-treated Oven-dried	10.1	48.0 (5.08)	2.1	0.677 (0.5044)+

a -- Each treatment group has a sample size of 26

b, c -- Numbers in parenthesis refer to standard deviation and significant probability, respectively.

* -- Significant at 95% level

** -- Highly significant

+ -- Not significant at 95% level

4.2.3.1 **Equilibrium moisture content (EMC)**

The EMCs of the water-treated and air dried specimens were slightly higher than the controls, but the differences were not statistically significant ($p > 0.05$). Bendtsen, *et al.*, (1983), Winandy (1989) and Barnes, *et al.*, (1990) also found slight, but statistically insignificant increases in the MC of water-treated and air dried small clear-wood specimens compared to untreated controls. The EMCs of the water-treated and oven dried specimens, particularly the bending test specimens, were significantly less than the controls and the water-treated and air dried specimens. It is well established that oven drying reduces the EMC of wood [Skaar, 1988] and this may explain the lower EMC of the water treated and oven dried specimens.

4.2.3.2 Modulus of elasticity (MOE)

The MOE of water-treated specimens increased by 7.0 and 10.4% (based on the property value of the control) after air and oven drying, respectively. Increases in MOE of treated specimens cannot be solely attributed to the effect of treatment on EMC. Oven dried specimens showed a lower EMC and a higher MOE. The EMC of the air dried specimens was higher than the controls but they also showed an increase in MOE. Like Gerhards (1968), experimental errors favouring one treatment more than others may have contributed in part to the increases in MOE.

Results of previous studies in this area vary. Bendtsen, *et al.*, (1983) reported an increase in MOE of water-treated samples after air drying, but MOE decreased after kiln drying (60 °C for 10 days). Winandy (1989) reported a decrease in MOE after air and kiln drying (115.5 °C for 6 h), while Barnes, *et al.*, (1990) reported a slight increase in MOE after kiln drying (rising DBT up to 92 °C for 66 h). All of these studies used small clear-wood southern pine specimens.

4.2.3.3 Modulus of rupture (MOR) and maximum crushing strength (MCS)

The MOR and MCS of the water-treated specimens decreased slightly after air and oven drying, but the decreases were statistically insignificant ($p > 0.05$). Thus, water treatment and re-drying by air or oven drying at 96.5 °C for 18 h has no adverse effect on MOR and MCS. The slight decreases in strength observed after treatment may be due to sampling variation. Bendtsen, *et al.*, (1983), Winandy (1989) and Barnes, *et al.*,(1990) have also observed a similar small decreases in

MOR of water-treated small clear-wood specimens after air and kiln drying. However, they gave no explanation to account for the losses in strength. No previous studies have been carried out to determine the effect of water treatment and re-drying on MCS.

4.2.4 Conclusion

Water treatment and re-drying had no deleterious effects on MOE, MOR and MCS of small clear-wood radiata pine specimens. MOE increased after water treatment and air and oven drying (96.5 °C for 18h).

4.3 Effect of heat (Oven drying)

4.3.1 Introduction

Heat, particularly in the presence of water and oxygen may cause hydrolysis and oxidation of the wood cell-wall [Mottet, 1982]. This may weaken wood, but it has been observed (see review of literature) that different wood species and grades vary in their response to heating temperature and exposure time. Radiata pine has been shown to tolerate temperatures above 115 °C for 15 to 16 hours without significant loss of strength [Hillis, 1984]. However, Hillis (1984) stated that some variation in strength loss may occur because of differences in the chemical and anatomical nature of radiata pine and due to differences in the methods of heating.

The object of this experiment was to examine the effect of heat (oven drying) on the MOE, MOR and MCS of small clear-wood radiata pine specimens.

4.3.2 Experimental procedure

The small clear-wood specimens used in this experiment were cut from the timber described in Section 4.1.2. Additional specimens were prepared from the timber described in Section 3.1.1. The preparation of specimens was described in Section 3.2.1. The design of the experiment is illustrated in Figure 4.4.

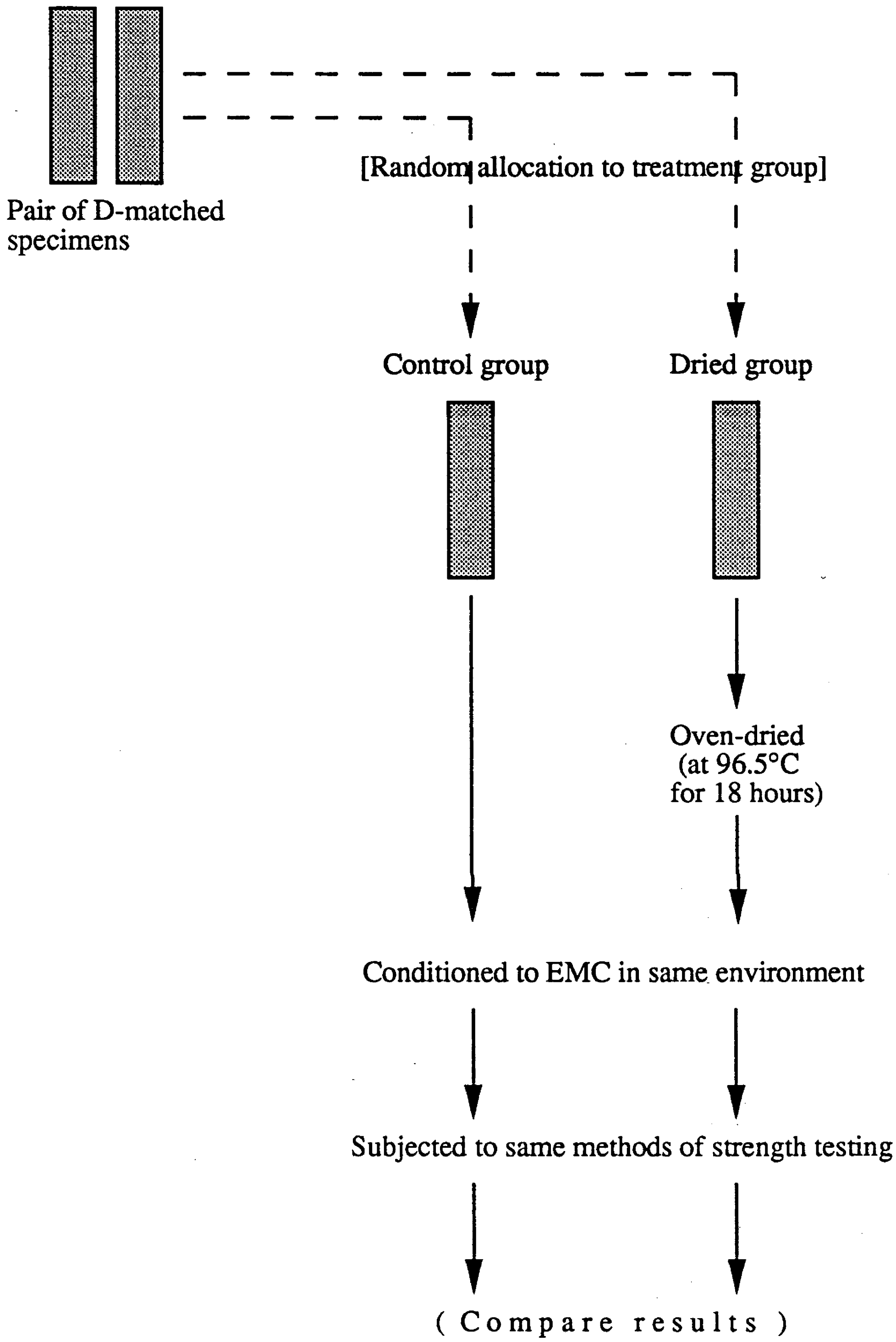


Figure 4.4 The experimental design used to evaluate the effect of heat (oven drying) on MOE, MOR and MCS of small clear-wood specimens

Two sets of 25 pairs of D-matched specimens were prepared. One set was used for bending tests and the other was used for compression tests. The 25 pairs of specimens in each set were randomly allocated to the experimental treatments, one pair at a time, with one piece allocated to one treatment group and the other matched piece allocated to the control.

4.3.2.1 Drying, conditioning and strength testing

The average MC of all conditioned specimens was about 12%. Untreated controls remained in a conditioning room at 20 ± 1 °C and 65 ± 5% RH until ready for testing. The bending and compression test specimens assigned to oven drying were dried in a laboratory oven at 96.5 °C for 18 hours. After drying, these specimens were allowed to cool and they were then placed in a conditioning room for four weeks until they attained a constant weight. Strength tests were then carried out as described in Sections 3.6.1 (bending test) and 3.6.2 (compression parallel to the grain test).

4.3.3 Results and discussion

The effect of oven drying on the strength properties of radiata pine are summarized in Table 4.3. After oven drying there was an increase in MOE of 6.4% but the increase was not statistically significant ($p > 0.05$). MOR and MCS increased by 10.3% and 10.6%, respectively. These increases were highly significant ($p < 0.01$). Similar trends have been observed in previous studies [Gerhards, 1968; Salamon, 1969; Beal, 1982] and the increases in strength following oven drying have generally been attributed to decreases in the EMC of the timber.

Heat treatment by oven drying at 96.5 °C for 18 h caused a reduction in the EMC of specimens. This effect also occured for oven-dried water-treated specimens [Table 4.2]. These decreases in EMC after heat treatment are consistent with the observations of Skaar (1972; 1988) who attributed them to loss of hygroscopicity as a result of thermal degradation of hemicelluloses.

Table 4.3 The effect of oven drying (96.5 °C) on the MOE, MOR and MCS of small clear-wood radiata pine specimens

Property	Treatment group [a]	EMC (%)	Strength (MPa)[b]	Strength change (%)	Paired t-value [c]
MOE	Control	13.0	10291.7 (2224.05)		
	Oven-dried	9.9	10948.7 (1883.34)	+6.4	-1.25 (0.2242)+
MOR	Control	13.0	90.8 (12.28)		
	Oven-dried	9.9	100.1 (14.60)	+10.3	-3.21 (0.0037)**
MCS	Control	11.0	48.6 (8.48)		
	Oven-dried	9.2	53.7 (7.14)	-10.6	-4.58 (0.0001)**

a -- Each experimental treatment group has a sample size of 25

b, c - Numbers in parenthesis refer to standard deviation and significant probability, respectively.

** -- Highly significant

+ -- Not significant at 95% level

A reduction in EMC is accompanied by strength increases resulting from increased hydrogen bonding between hydroxyl groups. Reductions in EMC may also decrease the effective section modulus of the specimens as a result of shrinkage. Section modulus is a function of cross-sectional dimensions of the specimens and is inversely related to MOE, MOR and MCS. It should be noted that the decreases in EMC in this experiment are greater than those observed earlier (Section 4.2) and may account for the increases in mechanical properties of specimens after oven drying.

4.3.4 Conclusions

Oven drying at 96.5 °C for 18 hours has no deleterious effect on the mechanical properties of small clear-wood radiata pine specimens and may increase MOR and MCS.

4.4 Designing treatments for subsequent experiments

Information obtained from these experiments was used to design treatments used in subsequent chapters. From strength data, the coefficient of variation (CV) of samples was determined and this was used to estimate the minimum number of samples for the experiments using small clear-wood specimens.

Since CCA treatment and mild air drying (Section 4.1), water treatment (Section 4.2) and heat treatment (Section 4.3) did not cause significant losses in the strength properties of wood specimens (with the exception of the effect of CCA treatment on MCS), it was suspected that strength losses in CCA treated wood may largely be due to the interaction of preservative treatment and re-drying at temperature greater than ambient condition. Hence further experiments examined the combined effects of CCA treatment and drying.

Although water treatment and re-drying did not cause strength losses in small clear-wood specimens, water-treated controls were included in subsequent experiments since tests on small clear specimens may not be relevant to structural size timber.

Chapter Five

EFFECT OF CCA TREATMENT AND RE-DRYING AT HIGH TEMPERATURE ON THE MECHANICAL PROPERTIES OF SMALL CLEAR-WOOD RADIATA PINE SPECIMENS

5.1 Introduction

Preliminary studies in Chapter 4 showed that CCA treatment and air drying caused small, but significant losses in the MCS of small clear-wood radiata pine specimens and, at a high treatment retention, increased MOR. Strength losses in CCA-treated timber during re-drying may be due to hydrolytic or oxidative degradatiion of the wood cell wall by the salt components of CCA [Winandy and Boone, 1988]. In accord with chemical kinetics, such degradation is likely to increase with an increase in the re-drying temperature and strength losses may be severe if the re-drying temperature is high (i.e., > 100 °C). It can be infered from previous studies with southern pine [Barnes, 1985; Winandy, *et al.*, 1985] that high temperature drying may cause significant strength losses in CCA-treated radiata pine. There have been no previous studies of the effect of high temperature drying on the strength properties of radiata pine and therefore one of the specific aims of the work in this chapter is to examine the strength changes in CCA-treated small clear-wood specimens after high temperature drying and to determine the extent to which different strength properties are affected by CCA treatment and re-drying.

Treatment of wood to high CCA retentions, makes it less permeable since cell lumens and pit cavities become blocked by the insoluble products of CCA fixation. As a results of such decreases in permeability, CCA-treated wood dries more slowly during kiln drying, shows steeper moisture gradients and is more degrade prone than untreated wood [Williams, 1974]. Such effects may in part be responsible for the strength losses that occur during the re-drying of timber treated to high CCA retentions. Higher retentions of CCA are achieved by treating timber with more concentrated CCA solutions and this may also lead to greater strength losses during re-drying due to the greater hydrolytic or oxidative capacity of the CCA solution. However, preliminary studies (Chapter 4) have shown that CCA treatment of small clear-wood radiata pine specimens to a high retention (37.46 kg m^{-3}), followed by air drying caused increases in MOR. To clarify the effect of treatment retention on strength changes of CCA-treated wood during re-drying, work was also undertaken to examine whether strength changes in CCA-treated small clear-wood specimens during high temperature re-drying are affected by treatment retention levels (high retention v low retention).

5.2 Experimental design and procedure

Two sets of small clear-wood specimens were cut from the timber samples prepared previously (Section 3.2.1). One set was used for bending tests and the other was used for compression tests. Each set consisted of 48 groups, containing 4 D-matched specimens per group. Each specimen in a group was randomly assigned to one of four experimental treatments; i.e., the untreated control, water-treated, CCA-treated low-retention and CCA-treated high-retention. Thus, each treatment group had a total of 48 small clear-wood specimens. Figure 5.1 illustrates the design of the experiment.

The groups assigned for CCA treatment were pressure treated as described previously (Section 3.3) using 2.4% (pH ~ 2.16) and 4.2% (pH ~ 1.85) CCA solutions for the low and high treatment retentions, respectively. Specimens assigned for water treatment were pressure treated using Canberra tap water. The untreated control specimens were placed in a conditioning room (Section 3.5).

After treatment, treated specimens including those treated with water, were allowed to `drip dry' for 24 to 36 h under cover before kiln drying. The kiln schedule used involved drying at 116 °C DBT and 82 °C WBT for 21 h followed by a 6 h equalization period at 76 °C DBT and 71°C WBT for a total kiln time of 27 h. The airs peed used during drying was 4.5 m s^{-1} with fan reversal every 3 h.

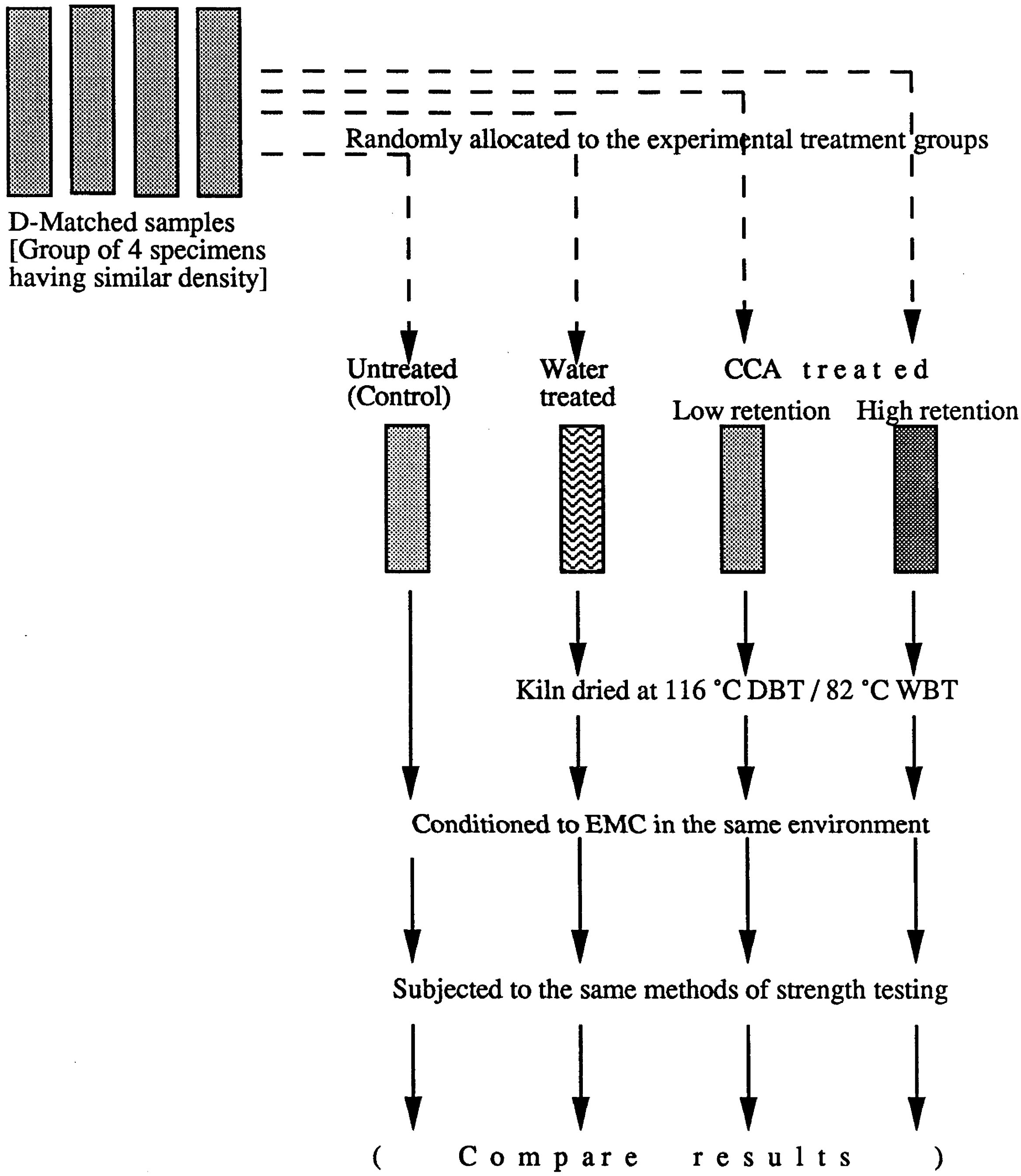


Figure 5.1 The design of the experiment to evaluate the effect of CCA treatment and re-drying at high temperature on the mechanical properties of small clear-wood radiata pine specimens.

Conditioning and strength testing of all specimens were carried out as described previously in Sections 3.5 and 3.6, respectively.

5.3 Results and discussion

The average retention of CCA-treated specimens as determined by X-ray fluorescence analysis was 19.3 kg m^{-3} for the low-retention group and 30.4 kg m^{-3} for the high-retention group.

The average MC of the control, water-treated, CCA-treated low retention and CCA-treated high retention bending specimens were 10.5%, 8.9%, 9.5% and 9.5%, respectively. The average MC of similarly treated and conditioned compression specimens were 10.6%, 8.9%, 9.7% and 10.3%, respectively. The decreases in EMC of the treated specimens after HTD are consistent with previous findings (Section 4.3) and with the observation of Winandy (1989). HTD reduced the EMC of specimens and this effect was most marked for the water treated specimens.

Strength test data were not adjusted for MC differences since all treatment groups were conditioned in the same environment and there is evidence that the reduction in hygroscopicity induced by HTD is permanent [Barnes and Mitchell, 1984; Winandy, 1989]. Exploratory statistical analysis of the strength data revealed a few units with large residuals or outliers. These values resulted from the testing of defective specimens and thus the data arising from the testing of these specimens were culled from the total data set. Since the experiments involved paired test specimens, the matching specimen from a culled data pair was also removed from the data. Four sets (i.e., 4 x 4 units) were removed from the MOR data, and three (i.e., 3 x 4 units) from the MOE data, but none were removed from the MCS data. The statistical analysis was not significantly altered by the removal of these outliers.

Table 5.1 summarize the results of the effect of CCA treatment and re-drying at high temperature on MOE, MOR and MCS. These results are also presented graphically in Figures 5.2a, 5.2b and 5.2c, respectively, to enable the results to be compared more easily. Each treatment mean is represented by a bar (shaded for identification) with their 95% confidence interval (represented by a line bar).

Table 5.1 The effect of CCA treatment and re-drying at high temperature on the mechanical properties of small clear-wood radiata pine specimens.

Property	Treatment Group	Retention (kg m^{-3})	EMC (%)	Strength Property mean (MPa) [a]	Strength change (%)	Paired t-value [b] (2-tail)
MOE	Control		10.5	10209.8 (2831.5)		
	Water-treated		8.9	10116.4 (2649.7)	-0.92	0.35 (0.725)+
	CCA-Low R	19.3	9.5	9886.1 (2707.6)	-3.2	1.18 (0.245)+
	CCA-High R	30.4	9.5	10175.5 (2992.2)	-0.34	0.13 (0.897)+
MOR	Control		10.5	60.9 (19.4)		
	Water-treated		8.9	61.8 (16.8)	+1.5	-0.48 (0.633)+
	CCA-Low R	19.3	9.5	42.0 (14.2)	-31.0	8.48 (0.0001)*
	CCA-High R	30.4	9.5	43.8 (14.0)	-28.1	7.20 (0.0001)*
MCS	Control		10.6	41.4 (8.6)		
	Water-treated		8.9	42.1 (9.0)	+1.6	-0.47 (0.637)+
	CCA-Low R	19.3	9.7	45.5 (9.0)	+9.8	-3.32 (0.002)*
	CCA-High R	30.4	10.3	45.1 (8.7)	+8.9	-3.37 (0.002)*

a, b - numbers in parenthesis refers to the standard deviation and significant probability, respectively.

* - highly significant at 95% confidence level

+ - not significant at 95% confidence level.

5.3.1 Modulus of elasticity (MOE)

After treatment and HTD (116 °C) the MOE of the water treated and the low and high retention CCA-treated specimens showed small statistically insignificant ($p > 0.05$) decreases of 93.4 MPa (0.92%), 323.7 MPa (3.2%) and 34.3 MPa (0.34%), respectively. These findings support previous work on the effect of CCA treatment and HTD on MOE. For example, Siemon (1979) found that treatment of small clear-wood Caribbean pine specimens with CCA to a retention of 16.0 kg m^{-3}, followed by re-drying at 120 °C had an insignificant effect on MOE.

The following combinations of CCA treatment retention and HTD are also reported to have no significant effect on the MOE of small clear-wood southern pine specimens (Table 2.2); 16.0 kg m^{-3} - 104.4 °C and 40.0 kg m^{-3} -104.4 °C [Winandy *et al.*, 1985], 9.6 kg m^{-3} -115.5 °C and 24.0 kg m^{-3} -115.5 °C [Barnes, 1985] and 4.8 kg m^{-3} - 115.5 °C [Mitchell & Barnes, 1986]. It appears tha these combinations of CCA treatment and HTD do not cause significant losses in the elastic properties of wood (e.g., MOE). However, Barnes (1985) found significant reductions in MOE of 7.5%, 12.9%, 11.0% and 10.0% when the following combinations of CCA retentions and HTD were applied to southern pine; 9.6 kg m^{-3} - 126.7 °C, 9.6 kg m^{-3} - 137.8 °C, 24.0 kg m^{-3} - 126.7 °C and 24.0 kg m^{-3} - 137.8 °C (Table 2.2). These findings indicate that at higher re-drying temperatures losses in MOE of CCA treated wood may occur. Apparently,

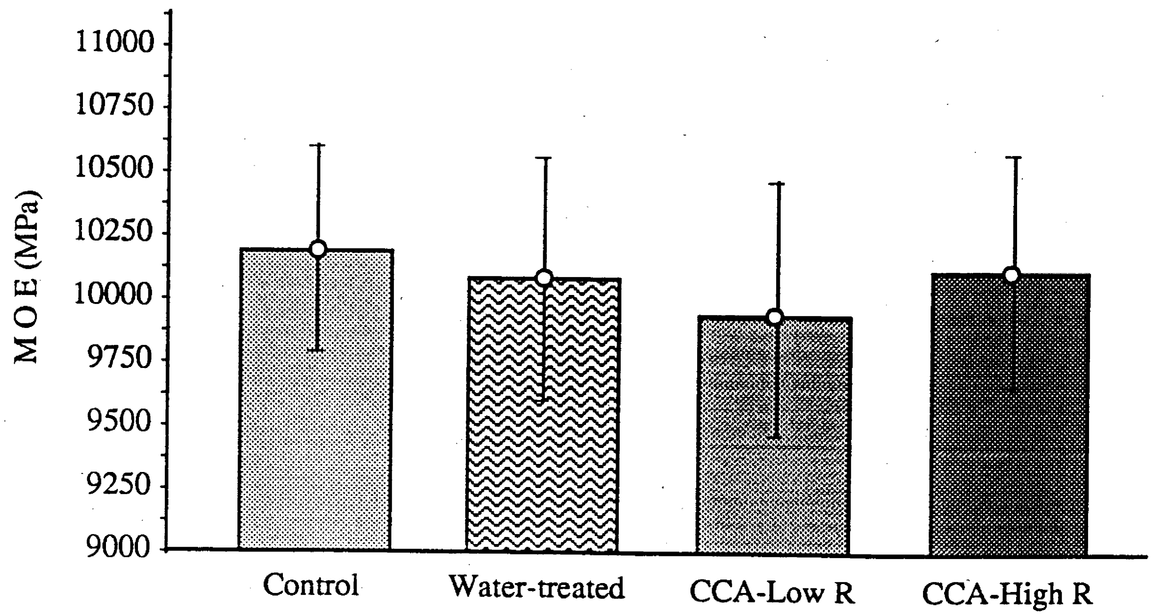


Figure 5.2a The mean MOE's for the four treatment groups of small clear-wood radiata pine specimens after HTD

higher temperatures and the presence of CCA are sufficent to cause significant hydrolysis of the wood cell walls. Degradation is catalyzed by CCA in wood and hydrolysis of the bonds between glucose monomers occurs causing degradation of the cellulosic microfibrils [Mitchell and Barnes, 1986].

Findings here and those reported previously suggest that re-drying temperature is more important than CCA retention in reducing the MOE of CCA-treated small clear-wood specimens after re-drying.

5.3.2 **Modulus of rupture (MOR)**

The MOR of the low and high-retention CCA-treated specimens decreased significantly ($p < 0.05$) by 18.9 MPa (31.0%) and 17.1 MPa (28.1%), respectively after HTD. There were no significant ($p > 0.05$) differences in the MOR of the low-retention and high-retention treated specimens.. Similarly, there were no significant differences in the MOR of the untreated controls and the water-treated specimens. The MOR of the water-treated group was significantly ($p < 0.05$) higher than the MOR of the CCA-treated groups.

The insignificant ($p > 0.05$) differences in the MOR of the low and high-retention groups suggest that treatment retention had little influence on strength losses of CCA-treated wood during HTD. However, the presence of CCA in the wood appears to be necessary for strength losses to occur during HTD, since water treated specimens did not differ significantly ($p > 0.05$) in strength from the untreated controls. Although previous results (Table 4.1a) showed that CCA treatment and air drying increased MOR, exposure to high temperatures during HTD may have increased the oxidative or hydrolytic degradation of the treated wood, resulting in significant strength losses.

Visual observation of treated and re-dried specimens showed that there were no significant defects in the CCA treated re-dried specimens, and therefore strength losses were probably due to the chemical action of the CCA rather than due to increases in drying degrade as a results of drying treated wood.

It thus appears that it is the interaction of CCA treatment and HTD that reduces MOR. Previous studies (Table 2.2) using small clear-wood southern pine specimens showed that MOR have decreased after CCA treatment and HTD. The magnitude of reductions appears to be better correlated with re-drying temperature than with treatment retention. For example, specimens treated to a retention of 9.6 kg m^{-3} and re-dried at 115.5 °C, 126.7 °C and 137.8 °C showed reductions in MOR of 9.7%, 20.5% and 32.9%, respectively. Whereas, the specimens treated to a retention of 24.0 kg m^{-3} and re-dried at 115.5 °C, 126.7 °C and 137.8 °C, showed reductions in MOR of 7.1 %, 11.9 % and 36.9 %, respectively [Barnes, 1985].

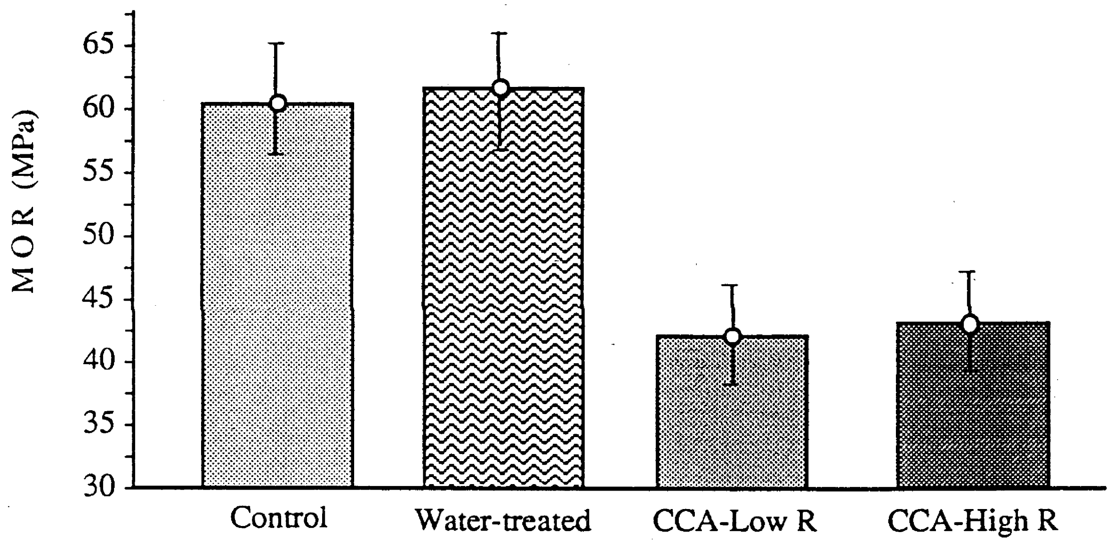


Figure 5.2b The mean MOR's for the four treatment groups of small clear-wood radiata pine specimens after HTD

5.3.3. Maximum crushing strength (MCS)

In accord with the results for MOR, there were no significant ($p > 0.05$) differences in the MCS of the CCA-treated and high temperature re-dried low and high-retention CCA specimens, or the untreated (control) and water-treated specimens. MCS of the CCA-treated specimens were significantly ($p < 0.05$) higher than the control.

The MCS of the low and high-retention CCA-treated specimens increased significantly ($p < 0.05$) after HTD by 4.1 MPa (9.8%) and 3.7 MPa (8.9%), respectively. These findings are contrary to the preliminary results in Chapter 4 and with those of Winandy, *et al.*, (1985) who reported a 9.0 % decrease in the MCS of small clear-wood southern pine specimens after CCA treatment (TR = 40.0 kg m^{-3}) and re-drying at 104.4 °C. The increase in MCS of the treated specimens may be related to the heat applied during HTD since preliminary findings (Chapter 4) indicated that CCA treatment and air drying caused losses in MCS.

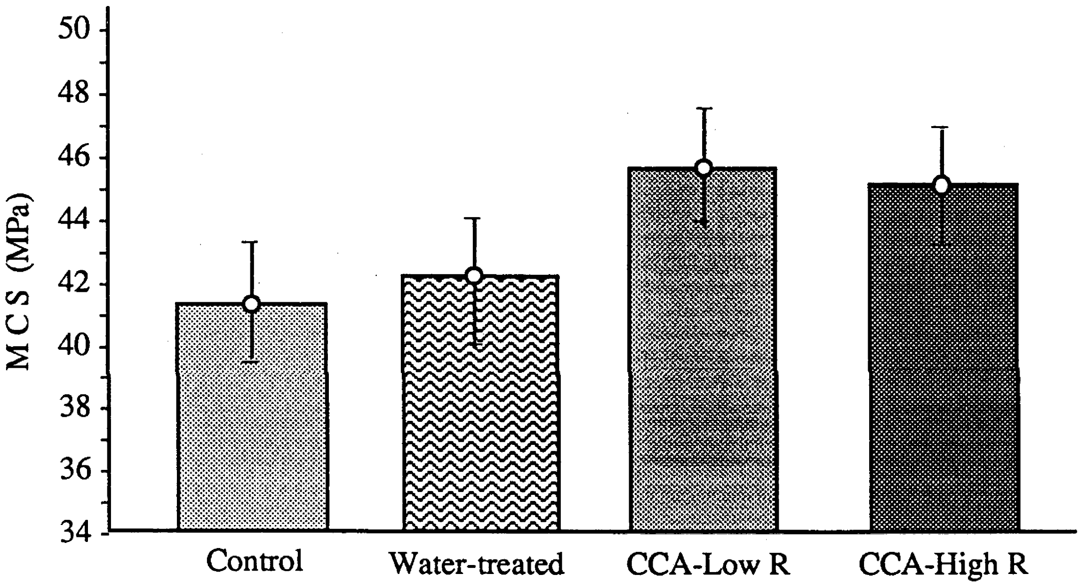


Figure 5.2c The mean MCS's for the four treatment groups of small clear-wood radiata pine specimens after HTD

5.3.4 Percentile distribution

It has been suggested that studies which only evaluate mean strength values may overlook the effect of CCA treatment and re-drying at the strength value used in formulating design values, i.e., the 5th percentile lower exclusion limit [Barnes and

Mitchell, 1984]. Hence, this study also evaluated the percentile distribution of strength properties after CCA treatment and HTD. Evaluation of the effect of treatment and re-drying on percentiles is limited to a simple comparison of the property values at a common point in the distribution. No valid statistical test of significance is yet available to compare percentile values [Barnes and Mitchell, 1984].

Based on a normal distribution, the cumulative percentile distributions of MOE, MOR and MCS for the different treatment groups are presented graphically in Figures 5.3a, 5.3b and 5.3c, respectively. Each treatment group is represented by a sigmoid curve or ogive. The position of an ogive in relation to the ogive of the untreated control group shows the effect of treatment and re-drying on the mechanical properties of the wood specimens. Thus, an increase in strength as a result of treatment and re-drying results an ogive lying above that of the control. Conversely, a reduction in strength results an ogive lying below that of the control.

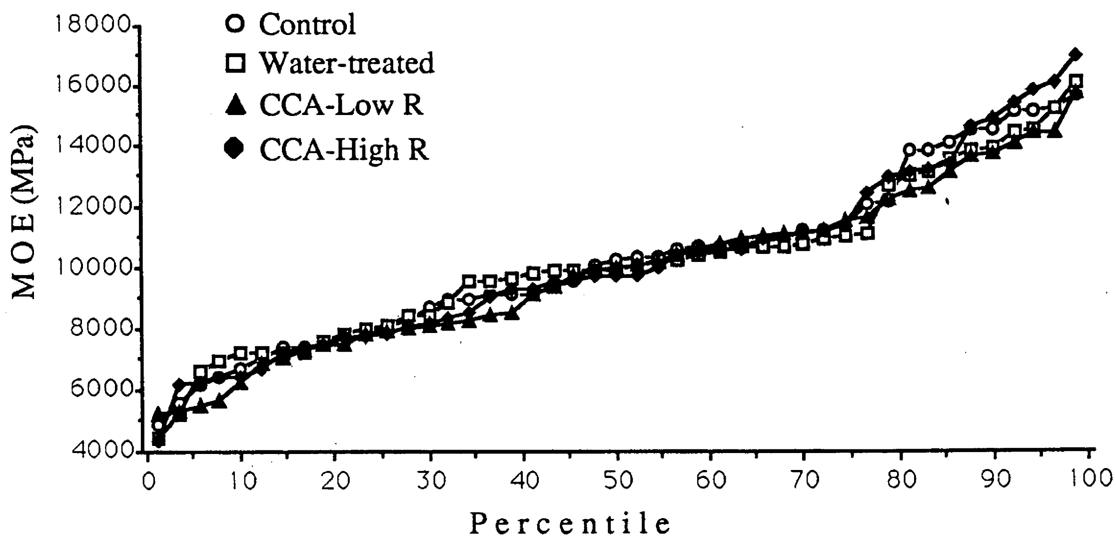


Figure 5.3a Cumulative percentile distribution of MOE for the three treated groups and the control group of small clear-wood radiata pine specimens kiln dried at 116 °C after treatment

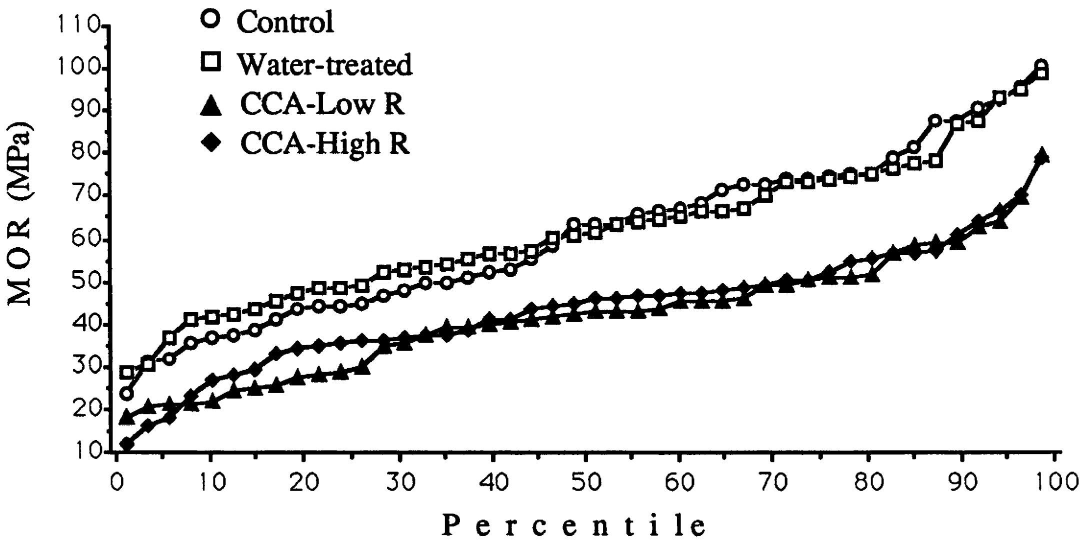


Figure 5.3b **Cumulative percentile distribution of MOR for the three treated groups and the control group of small clear-wood radiata pine specimens kiln dried at 116 °C after treatment**

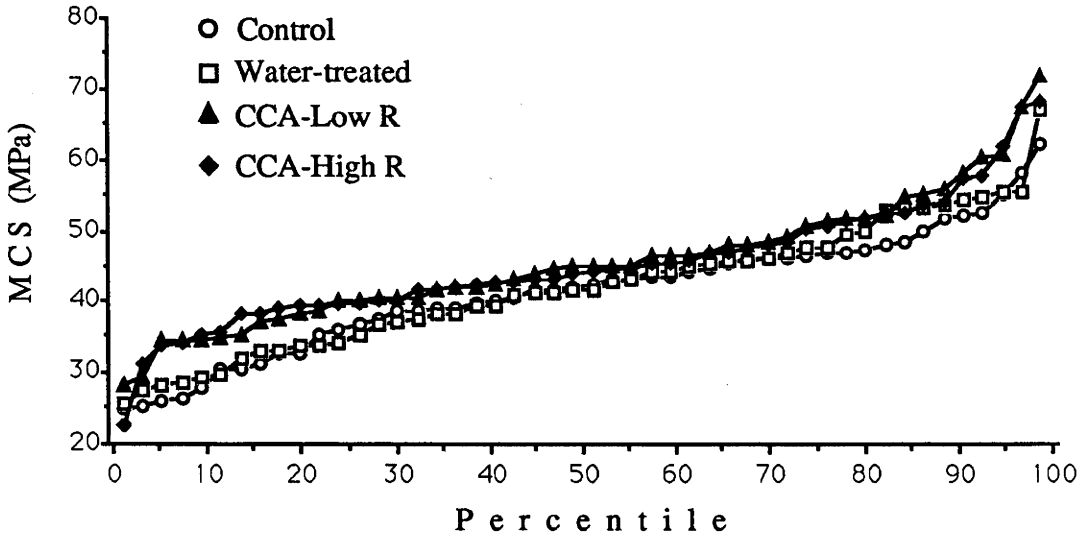


Figure 5.3c **Cumulative percentile distribution of MCS for the three treated groups and the control group of small clear-wood radiata pine specimens kiln dried at 116 °C after treatment**

The property values at selected points (percentiles) of the property distribution for each treatment group are presented in Table 5.2. Strength losses expressed as a percentage of the corresponding property value of the control group are also presented.

Table 5.2 The MOE, MOR and MCS (in MPa) of small clear-wood treated and re-dried radiata pine specimens at selected percentile of the property distribution.

Property	Treatment Group	Percentile 5th	10th	25th	50th	75th
MOE	Control	5552.0	6713.4	8052.2	10251.5	11552.6
	Water-treated	5757.6 (+3.7)	7194.4 (+7.2)	8032.3 (-0.25)	9949.6 (-2.9)	11068.5 (-4.2)
	CCA-Low R	5432.1 (-2.2)	6248.5 (-6.9)	7891.6 (-2.0)	10017.0 (-2.3)	11592.7 (+0.35)
	CCA-High R	5253.4 (-5.4)	6464.2 (-3.7)	7833.9 (-2.7)	9774.7 (-4.6)	11669.3 (+1.0)
MOR	Control	29.0	36.4	44.2	63.4	74.5
	Water-treated	34.2 (+18.0)	41.7 (+14.3)	48.9 (+10.6)	61.4 (-3.1)	73.7 (-1.0)
	CCA-Low R	18.6 (-35.7)	21.8 (-40.1)	29.3 (-33.8)	42.7 (-32.7)	50.7 (-32.0)
	CCA-High R	20.8 (-28.2)	26.5 (-27.2)	36.0 (-18.7)	45.4 (-28.4)	51.2 (-31.2)
MCS	Control	27.4	28.6	36.4	42.3	46.7
	Water-treated	27.2 (-0.55)	29.5 (+3.1)	34.7 (-4.7)	41.6 (-1.4)	47.6 (+1.9)
	CCA-Low R	30.6 (+11.9)	34.8 (+21.7)	40.2 (+10.4)	44.9 (+6.2)	51.0 (+9.2)
	CCA-High R	30.8 (+12.6)	35.4 (+23.7)	39.9 (+9.5)	43.9 (+4.0)	50.3 (+7.7)

Note: Numbers in parenthesis are percent strength changes based on the property value of the control group. Numbers preceded by a negative sign (-) indicate a loss in strength and those preceded by a positive sign (+) indicate a gain in strength.

The effect of CCA treatment and HTD on mechanical properties can be estimated from the strength losses at different percentiles. Losses in MOE at selected percentiles of the property distribution are relatively small compared to losses in MOR. For example, at the 5th percentile, losses in MOE for CCA-treated low-retention and high-retention groups were only 2.2% and 5.4% respectively, whereas, losses in MOR for similarly treated specimens were 35.7% and 28.2%, respectively. The same trend is shown at higher percentiles of the property distribution (Table 5.2). This indicates, in accord with previous results, that MOR is reduced to a greater extent by treatment and HTD than MOE.

The MCS of the CCA-treated specimens at the various percentiles increased. For example, MCS for the CCA-treated low-retention group increased by 11.9% at the 5th percentile, 21.7% at the 10th percentile, 10.4% at the 25th percentile and 6.2% at the 50th percentile. Similarly, MCS for the CCA-treated high-retention group increased by 12.6%, 23.7%, 9.5% and 4.0% at the 5th, 10th, 25th and the 50th percentile, respectively.

If the mean losses of MOE, MOR and MCS (Table 5.1) are compared with those at the 5th percentile (Table 5.2), it is apparent that the latter were a little higher. For example, the mean losses for MOE were 3.2% and 0.3% for the CCA-treated low-retention and high-retention groups, respectively, whereas, the corresponding values in the 5th percentile were 2.2% and 5.4%. For MOR, the mean losses were 31.0% and 28.1% for the CCA-treated low-retention and high-retention groups, respectively, whereas, the corresponding values in the 5th percentile were 35.7% and 28.2%. For MCS, the mean increases in strength were 9.8% and 8.9% for the CCA-treated low-retention and high-retention groups, respectively and the corresponding values at the 5th percentile were 11.9% and 12.6%. Barnes and Mitchell (1984) have also observed greater strength reduction in CCA-treated and re-dried small clear-wood specimens at the 5 percent lower exclusion limit. This suggests that calculatiion of mean strength losses may underestimate the effect of CCA treatment and re-drying on strength losses at the 5th percentile.

5.4 Conclusions

The effect of CCA treatment and re-drying at high temperature on the mechanical properties of small clear-wood radiata pine specimens varied depending upon the strength property evaluated. Drying CCA treated specimens at 116 °C caused significant ($p < 0.05$) reductions in MOR. MOE showed a slight, but statistically insignificant decreased after CCA treatment and re-drying. In contrast, the MCS of CCA treated specimens increased after HTD.

Treatment retentions had little effect on the strength properties of CCA-treated specimens after HTD. However, the presence of the preservative in the wood during HTD was necessary for strength changes to occur since water-treated specimens subjected to HTD showed no significant ($p > 0.05$) change in strength properties.

Evaluation of the effect of CCA treatment and HTD on the MOE, MOR and MCS using percentile distributions indicated that strength losses were slightly higher when estimated using percentiles than when mean values were used.

Chapter Six

EFFECT OF CCA TREATMENT AND RE-DRYING AT HIGH TEMPERATURE ON THE MODULUS OF ELASTICITY AND MODULUS OF RUPTURE OF STRUCTURAL SIZE RADIATA PINE TIMBER

6.1 Introduction

The preceding Chapters (Chapters 4 and 5) examined the effect of CCA treatment and re-drying on the mechanical properties of small clear-wood radiata pine specimens. There is some doubt that strength values obtained from testing such small clear-wood specimens are directly applicable to structural size timber [Madsen and Eng, 1984; Bolden, 1991]. It has previously been assumed that CCA treatment and re-drying causes strength losses in timber by degrading the chemical constituents of wood, i.e., cellulose and lignin. If such an assumption is correct then it should be possible to relate strength losses occuring in small clear-wood specimens, to those occuring in structural size timber after CCA treatment and re-drying, since the chemical constituents of both are identical. However, if strength losses in timber after CCA treatment and re-drying are caused by an interaction of the treatments with defects, i.e., knots, sloping grain, pith material etc., which are present in structural size timber but absent from small clear-wood specimens then there will not necessarily be a relationship between strength losses occurring in small clear-wood specimens and those occurring in structural size timber after CCA treatment and re-drying. If the latter is correct then tests using small clear-wood specimens may have little value in predicting the behavior of structural size timber.

This chapter evaluates the effect of CCA treatment and high temperature re-drying (HTD) on the MOE and MOR of structural size radiata pine timber. The aims were to determine the effect of CCA treatment and HTD on strength properties and to establish whether strength losses in structural size radiata pine can be related to those observed in similarly treated small clear-wood specimens (Chapter 5).

6.2 Experimental procedure

The structural size timber samples used were those described in Section 3.1.1. The experimental design used was similar to that described in Chapter 5 (Figure 5.1) except that E-matched structural size timber (see Section 3.2.2) was used.

Sixty (60) groups were prepared, containing 4 E-matched timber samples per group. Each sample in a group was randomly allocated to one of four experimental treatments. The treatments used were identical to those described previously in Section 5.2 for the small clear-wood specimens (i.e., the CCA-treated low-retention, CCA-treated high-retention, water-treated and the untreated control).

Timber samples assigned for CCA treatment were pressure treated as described in Section 3.3 using a 2.4% (pH~1.88) or 4.2% (pH~1.85) CCA solution for the low and high treatment retention groups, respectively. Timber samples assigned for water treatment were pressure treated as above using Canberra tap water. The untreated control specimens were boxed piled under cover at ambient conditions.

After treatment, all treated timber samples were boxed piled under cover using 25 mm stickers to 'drip dry' for about 36 - 40 hours before kiln drying. The kiln schedule involved drying at 116 °C DBT and 82 °C WBT for 21 h followed by a 6 h equalization period at 76 °C DBT and 71 °C WBT to give a total kiln time of 27 hours. The air speed during drying was 4.5 m s^{-1} with a fan reversal every 3 h. Timber samples were kiln dried with restraint on top of the stack throughout the entire drying period. The restraining weights consisted of two pieces of steel, 130 x 600 x 2400 mm, permanently bolted together, weighing 1460 kg.

Prior to strength testing, timber samples were conditioned as described in Section 3.5. The presence of degrade after drying, such as checks, was noted. Strength testing was carried out as described in Section 3.6.1 taking note of the mode of failure of every test specimen. CCA retentions were determined as described in Section 3.7.2. Data were statistically analyzed as described in Section 3.9.

6.3 Results and discussion

The average MC of the timber samples at the time of strength testing were 10.7%, 11.7%, 11.6% and 10.8% for the untreated control, re-dried water-treated, re-dried CCA-treated low-retention and re-dried CCA-treated high-retention groups, respectively. The average CCA retentions for the low and high retention groups were 19.1 kg m^{-3} and 31.6 kg m^{-3}, respectively. Results of strength testing and statistical analysis of data for the different experimental treatments are summarized in Table 6.1. After exploratory data analysis, four sets from the total data set (i.e., 4 x 4 treatment groups) that had large residuals were discarded.

Table 6.1 The effect of CCA treatment and re-drying at high temperature on the MOE and MOR of structural size radiata pine timber.

Property	Treatment group	Retention (kg m^{-3})	EMC (%)	Strength Property Mean (MPa) [a]	Strength loss (%)	Paired t-value (2-tail) [b]
MOE	Control		10.7	9897.9 (2502.4)		
	Water-treated		11.7	9827.3 (2750.7)	0.7	0.27 (0.786)+
	CCA- Low R	19.1	11.6	9808.6 (2796.1)	0.9	0.40 (0.692)+
	CCA-High R	31.6	10.8	9818.4 (2464.2)	0.8	0.34 (0.738)+
MOR	Control		10.7	37.7 (14.7)		
	Water-treated		11.7	35.8 (16.0)	5.0	0.93 (0.355)+
	CCA-Low R	19.1	11.6	27.1 (13.6)	28.1	5.64 (0.0001)*
	CCA-High R	31.6	10.8	24.7 (11.9)	34.5	6.42 (0.0001)*

a, b - numbers in parenthesis refer to the standard deviation and significant probability, respectively.

* - highly significant

\+ - not significant at 95% confidence level

The effect of CCA treatment and re-drying on MOE and MOR are also presented graphically in Figures 6.1a and 6.1b, respectively, to enable the effect of treatment on strength to be compared more easily.

6.3.1 **Modulus of elasticity (MOE)**

MOE was not significantly affected by CCA treatment and HTD. After CCA treatment and re-drying at high temperature, MOE in the low and high retention groups was reduced by only 89.3 MPa (0.9%) and 79.5 MPa (0.8%), respectively. Treatment retention had no significant ($p > 0.05$) effect on loss of MOE after HTD. The MOE of the water-treated group was not significantly ($p > 0.05$) different from the control group. These results are consistent with those reported for small clear-wood specimens in the preceding chapter (Table 5.1).

Barnes and Mitchell (1984), Lee (1985), Winandy and Boone (1988) and Winandy (1989) also found that the MOE of structural size southern pine timber was not adversely affected by CCA treatment and re-drying up to 115.5 °C. In contrast, Barnes and Moore (1987) found a small (2.3%), but statistically significant ($p < 0.05$) increase in the MOE of structural size southern pine timber after CCA treatment ($R = 4.0$ kg m^{-3}) and re-drying at 121.1 °C.

6.3.2 **Modulus of rupture (MOR)**

After HTD the MOR of CCA treated timber was reduced significantly ($p < 0.05$) by 10.6 MPa (28.1%) and 13.0 MPa (34.5%) in the low and high-retention groups, respectively. There was no significant ($p > 0.05$) effect of CCA retention on MOR after HTD, but the presence of CCA does help to occur in strength losses since the MOR of the water-treated group was not significantly ($p > 0.05$) different from the untreated controls. Again, these results are consistent with those reported previously (Chapter 5) for small clear-wood specimens.

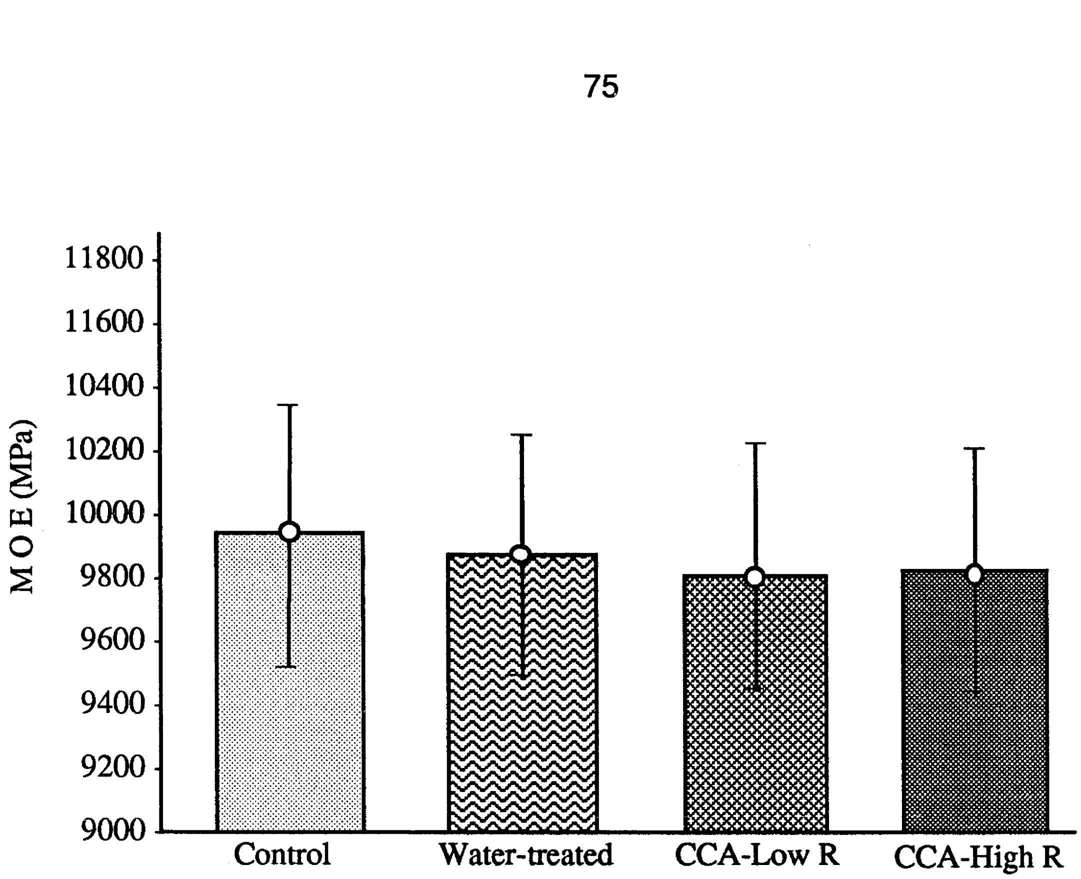


Figure 6.1a The mean MOE's for the control and the three treated groups of structural size radiata pine timber after HTD

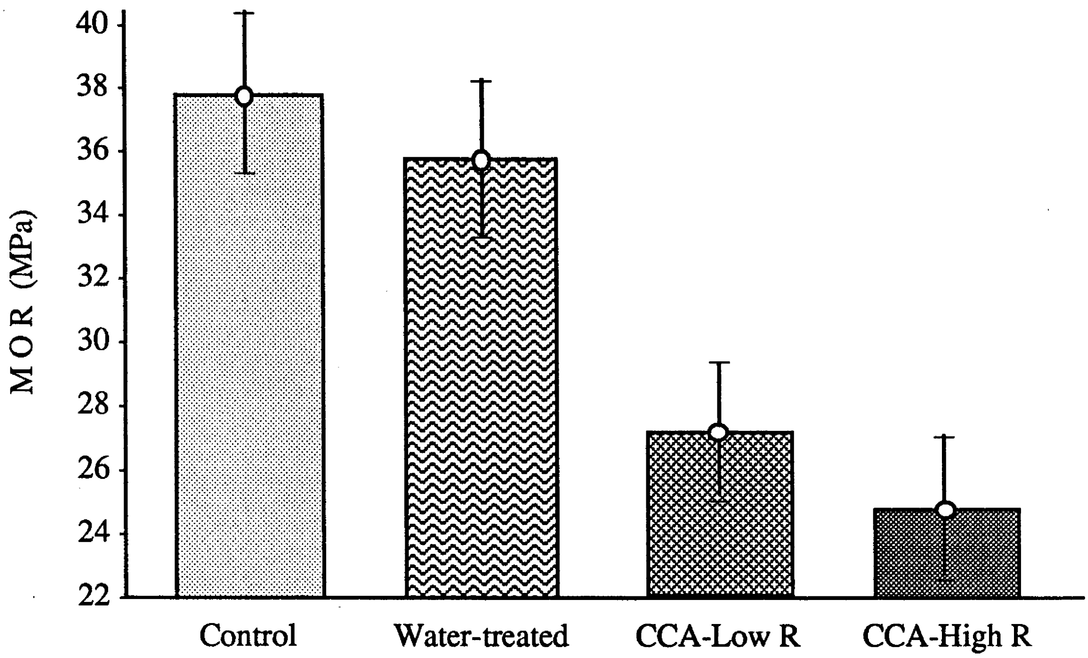


Figure 6.1b The mean MOR's for the control and the three treated groups of structural size radiata pine timber after HTD

Comparison of the strength of small clear-wood specimens and structural size timber after CCA treatment and re-drying reveals (Table 6.2) that the MOR of the former are higher. However, the percentage strength losses for both types of specimen are similar. Furthermore, for both types of specimens, statistical analysis of the effect of CCA treatment and re-drying on MOE and MOR reveal similar trends. Figures 5.2b and 6.1b which show the MOR of small clear-wood specimens and structural size timber after CCA treatment and HTD are remarkably similar.

Table 6.2 Change in MOR of small clear-wood specimens and structural size radiata pine timber after CCA treatment and high temperature drying (HTD)

Specimen Type	Treatment Group	Retention ($kg\ m^{-3}$)	MOR (MPa)	Strength change (%)
Small Clear-wood	Control		60.9	
	Water-treated		61.8	-1.48 +
	CCA-Low R	19.3	42.0	31.00*
	CCA-High R	30.4	43.8	28.07*
Structural size	Control		37.7	
	Water-treated		35.8	5.040 +
	CCA-Low R	19.1	27.1	28.12*
	CCA-High R	31.6	24.7	34.48*

* Significant at 95% level

\+ Not significant at 95% level

Previous studies [see Table 2.3] have also shown reductions in the MOR of structural size southern pine timber after CCA treatment and HTD. For example, Barnes and Mitchell, (1984) found a small, but statistically significant ($p < 0.05$) decrease of 11.6% in the MOR of CCA treated southern pine timber after HTD.

As suggested for the small clear-wood specimens (Section 5.3.2) the decrease in MOR of CCA treated structural size radiata pine timber after HTD is probably due to the interaction of CCA treatment and drying. It was noted that a greater proportion of CCA treated and re-dried timber specimens failed during testing in a brash manner compared to the water treated and re-dried timber specimens and untreated controls (Table 6.3). Figure 6.2 shows examples of the pattern of curves indicating the mode of failures of test specimens. Brash failure of bending test specimens is characteristic of wood that has undergone chemical or thermal degradation and therefore the greater proportion of brash failures in the CCA-treated group indicates that chemical degradation of these specimens may have occured. This suggests that strength losses in the treated timber during re-drying were due to the chemical/thermal effects of CCA treatment and re-drying on wood.

Table 6.3 The failure patterns of structural size timber after treatment and HTD.

Treatment groups [a]	Abrupt failure	Fibrous failure
Control	24	36
Water-treated	20	40
CCA Low-R	26	34
CCA High-R	34	26

a - Each group consisted of 60 specimens.

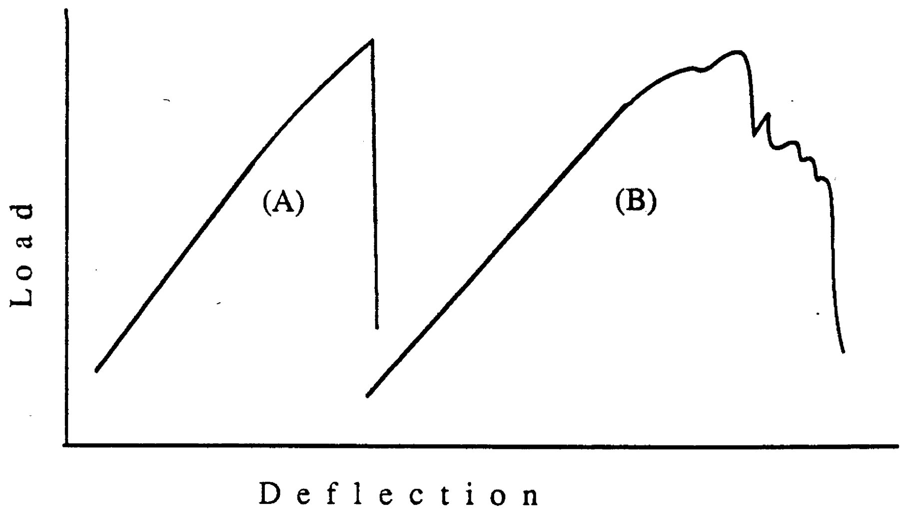


Figure 6.2 Load versus deflection curves for abrupt and fibrous failures (A) Abrupt failure, characterized by brashness of the fracture surface. (B) Fibrous failure, characterized by splintering of the fracture surface.

After bending tests were completed specimens were examined for surface checks. Specimens were also sawn into sections and examined for the presence of internal checks. There was little evidence to suggest that seasoning defects (checks) influenced the MOR of the treated and re-dried specimens. It should be noted that the structural timber specimens used here had been previously kiln dried to 12% MC at 120 °C DBT/ 90 °C WBT (Section 3.1.1) and therefore they may have contained some seasoning defects prior to treatment. However, it was noted that there were a number of instances where specimens which had more surface checks than their matched pieces failed at higher strength values. It therefore appears likely that drying degrade play little role in strength losses that occur during the HTD of CCA-treated structural size radiata pine timber.

6.3.3 Percentile distribution

The effect of CCA treatment and re-drying on MOE and MOR was also evaluated using the percentile distribution of the mechnanical properties. This was undertaken in order not to overlook treatment effects, particularly at the point used in formulating design values, i.e., the 5th percentile [Barnes and Mitchell, 1984].

The various percentile estimates of MOE and MOR for the different treatment groups are shown in Table 6.4, including the strength losses expressed as a percentage of corresponding controls. The complete percentile distribution of MOE and MOR for the different treatment groups are also shown in Figures 6.3a and 6.3b. These graphs illustrate how the treated samples compare with the controls across the entire strength distribution.

It can be seen from Table 6.4 that the effect of CCA treatment and re-drying on MOE and MOR varies across the percentile distribution. For example, the MOE for the CCA-treated high-retention group decreased by 0.3% at the 5th percentile, but showed an increase of 11.2% at the 10th percentile. MOE also decreased by 4.5% and 7.2% at the 25th and 50th percentile, respectively, but increased by 1.4% at the 75th percentile. Variation in the losses of MOR across the percentile distribution are more consistent. For example, for the CCA-treated high-retention group, MOR decreased by 62.0%, 48.7%, 44.9%, 36.5% and 38.1%, at the 5th, 10th, 25th, 50th and 75th percentile, respectively.

Table 6.4 The MOE and MOR (in MPa) of treated and high temperature re-dried structural size radiata pine timber at selected percentiles of the property distribution.

Property	Treatment group	Percentile 5th	10th	25th	50th	75th
MOE	Control	5781.5	6216.2	8187.0	10032.3	11805.4
	Water-treated	5302.3 (-8.3)	6145.6 (-1.1)	8053.1 (-1.6)	9753.4 (-2.8)	11834.3 (+0.2)
	CCA-Low R	5209.1 (-9.9)	6689.8 (+7.6)	7565.0 (-7.6)	9488.1 (-5.4)	11494.7 (-2.6)
	CCA-High R	5764.7 (-0.3)	6911.9 (+11.2)	7819.5 (-4.5)	9312.2 (-7.2)	11975.7 (+1.4)
MOR	Control	13.5	18.4	27.7	37.9	49.3
	Water-treated	9.4 (-30.3)	17.7 (-3.8)	22.3 (-19.5)	33.4 (-11.7)	49.2 (-0.2)
	CCA-Low R	4.6 (-65.8)	11.3 (-38.4)	15.4 (-44.2)	25.0 (-34.1)	38.4 (-22.1)
	CCA-High R	5.1 (-62.0)	9.4 (-48.7)	15.2 (-44.9)	24.1 (-36.5)	30.5 (-38.1)

Note: Numbers in parenthesis are percent strength changes based on the property value of the control group. Numbers preceded by a negative sign (-) indicate a loss in strength and those preceded by a positive sign (+) indicate a gain in strength.

In the absence of a valid statistical significance test for comparing strength values at various percentiles [Barnes and Mitchell, 1984; Winandy, 1989], an estimated value was used. Winandy (1989) suggested that a 10 percent difference in strength values across the percentile distribution could be used as a practical test of the significance of differences between treatment groups. He based the 10 % value on Tukey tests on strength data which indicated that differences in strength between treatments of 7 to 15 percent were significantly different at the 95% significance level.

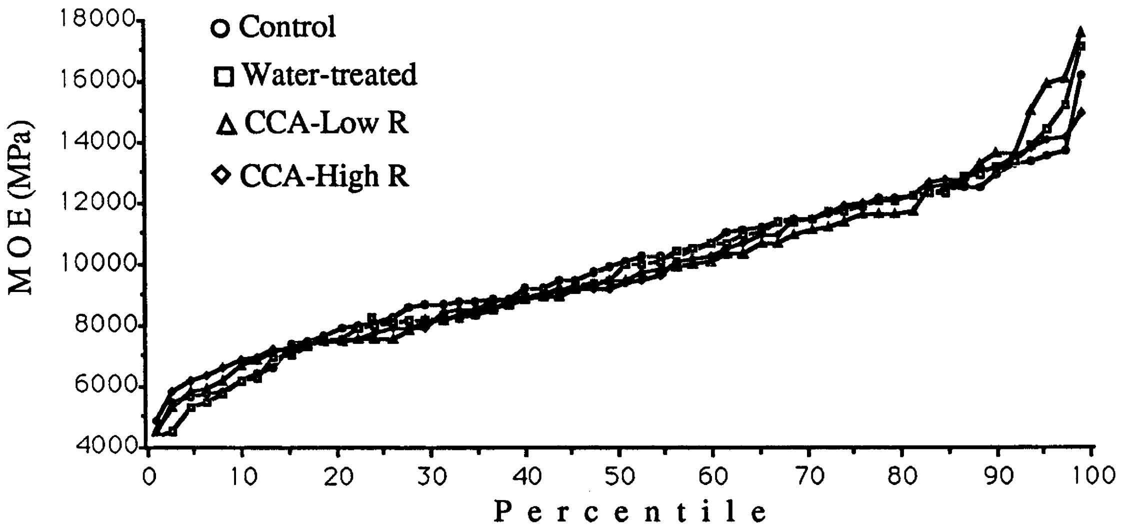


Figure 6.3a Cumulative percentile distribution of MOE for the three treated groups and the control group of structural size radiata pine timber kiln dried at 116°C after treatment

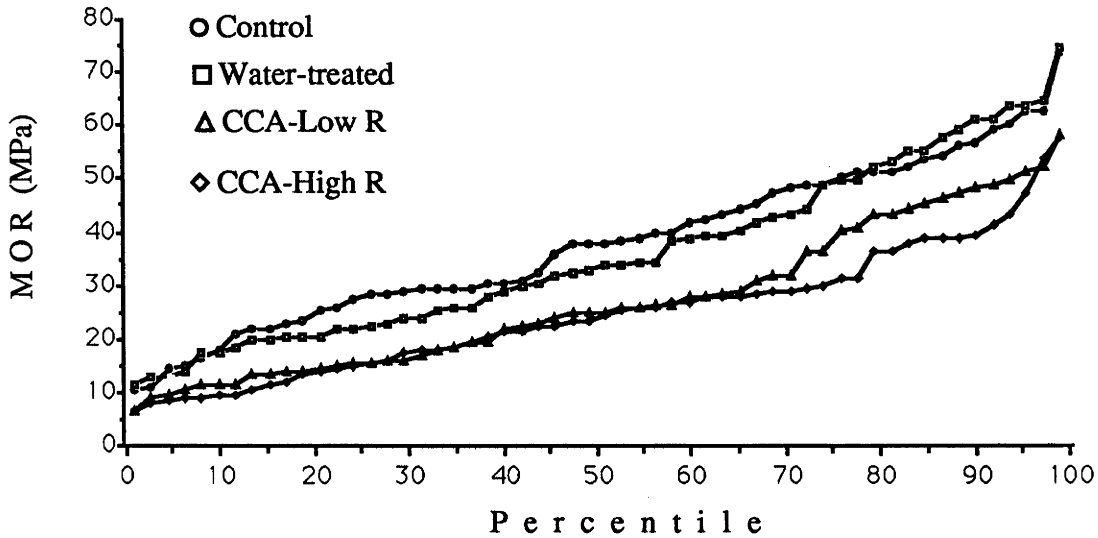


Figure 6.3b Cumulative percentile distribution of MOR for the three treated groups and the control group of structural size radiata pine timber kiln dried at 116°C after treatment

The MOE of treated and re-dried groups varied along the strength percentile distribution, but decreases or increases were generally not greater than 10% and hence were not significant. The greatest decrease in MOE after treatment and re-drying was 9.9%, observed at the 5th percentile for the CCA-treated low-retention group and the greatest increase was 11.2% observed at the 10th percentile for the CCA-treated high-retention group. Only the latter is significant. Previous studies [Barnes and Mitchell, 1984; Winandy and Boone, 1988; Winandy, 1989] have also found insignificant effects of CCA treatment and re-drying, either by air drying, conventional kiln drying or HTD on the MOE of structural size southern pine timber.

MOR showed decreases across the percentile strength distribution after CCA treatment and HTD of 22.1 to 65.8% and 36.5 to 62.0% for the low-retention and high-retention groups, respectively. Reductions in MOR were greater across the percentile distribution, particularly at the 5th percentile (Table 6.4), than in mean property values (Table 6.1).

Barnes and Mitchell (1984) found a significant reduction (8.3%) in the mean MOR of structural size southern pine timber after CCA treatment and conventional kiln drying (or LTD), and an 11.6% reduction when treated timber was re-dried at a high temperature (115.5 °C). Reductions in MOR were greater at the 5th percentile lower exclusion limit. CCA treatment followed by LTD (87.8°C) or HTD (115.5 °C) reduced MOR by 13.6% and 19.3% respectively at the 5th percentile [Barnes and MItchell, 1984]. In contrast, Winandy and Boone (1988) found that the MOR of southern pine timber (No. 2-Ongrade) was reduced from the 10th percentile onwards after CCA treatment and re-drying, but strength losses calculated using strength values obtained from the percentile distribution were less than those calculated using mean values. The latter study found that the average reduction in MOR was 6.9% - 7.5% for timber treated to 6.4 kg m^{-3} retention and 5.6% - 10.8% for timber treated to 9.6 kg m^{-3} retention. CCA treatment and HTD also had a negligible effect on the lower portion of the MOR distribution (i.e., < 10th percentile) including the 5th percentile. Winandy and Boone (1988) were surprised by these results, as they expected larger reductions in the lower portion of the strength distribution than in the average values. Differences in experimental details between their experiment and earlier studies [Barnes and Mitchell, 1984; Knuffel, 1985] were thought to account for the conflicting results.

While the findings here are consistent with those of Barnes and Mitchell (1984) they conflict with those of Winandy and Boone (1988), particularly when the effects of treatment and re-drying on MOR are compared at the 5th percentile. It should be noted that this experiment used structural size (F5) radiata pine timber and a CCA-Type C preservative treatment. Both of the previous studies mentioned have used structural size southern pine timber, but Barnes and Mitchell (1984) used a CCA-Type A preservative, while Winandy and Boone (1988) used a CCA-Type C preservative.

6.4 Conclusions

CCA treatment and HTD had negligible effects on the mean MOE and percentile distribution of structural size radiata pine timber. Treatment retention had no significant effect on MOE. These findings are consistent with earlier results (Chapter 5) on small clear-wood specimens.

MOR decreased significantly ($p < 0.05$) after CCA treatment and re-drying at high temperature (116 °C). Treatment retention had no effect on MOR. Large strength losses were observed both in the mean value and in the percentile strength distribution. This should merit consideration when formulating design values, particularly at the 5th percentile lower exclusion limit. Losses in MOR of structural size radiata pine after CCA treatment and re-drying were consistent with the results obtained using small clear-wood specimens (Chapter 5).

Chapter Seven

EFFECT OF CCA TREATMENT AND RE-DRYING AT LOW TEMPERATURE ON THE MODULUS OF ELASTICITY AND MODULUS OF RUPTURE OF STRUCTURAL SIZE RADIATA PINE TIMBER

7.1 Introduction

Results in the literature and those reported in the previous Chapter reveal that re-drying at a high temperature has little effect on the MOE of CCA-treated structural size timber. However, CCA treatment followed by HTD caused significant losses in the MOR of structural size radiata pine specimens. Re-drying of CCA-treated timber at lower temperatures may result in lower losses in MOR, but previous results on the effect of CCA treatment and re-drying at low temperature on the MOR of structural size timber are not consistent. Both Lee (1985) and Winandy *et al.*,(1985) found that CCA treatment and air drying had an insignificant ($p > 0.05$) effect on the MOR of structural size southern pine timber, but Winandy (1989) found that there was a significant ($p < 0.05$) reduction in the MOR of structural size southern pine timber after CCA treatment and air drying.

The aim of the work reported in this Chapter is to determine the efffect of CCA treatment and re-drying at low temperature on the bending properties of structural size radiata pine timber. The treatment retentions and drying regimes used were selected to resemble the current recommended approach [AS 1604 -1980; Kininmonth and Williams, 1974] in industry to the drying of CCA-treated structural size radiata pine timber.

7.2 Experimental design and procedure

Sixty (60) groups of samples (4 E-matched timber samples per group) were prepared from the stock used previously (Chapter 6). The experimental design used is illustrated in Figure 7.1. The allocation of samples to the experimental treatments was similar to that described in Section 5.2. The experimental treatments were; untreated controls, water-treated and kiln dried, CCA-treated and air dried, and CCA treated and kiln dried.

Timber samples assigned to CCA treatment were pressure treated as described previously (Section 3.3) using a 2.0% (pH~ 2.08) CCA solution. The timber samples assigned for water treatment were similarly treated using tap water.

After CCA treatment, treated samples assigned for air drying were box-piled under cover using 25 mm stickers to air dry at ambient condition (~ 22°C ± 5°C, RH~ 58% ± 3%) from August to November 1992. CCA-treated and water-treated samples assigned to kiln drying were similarly box-piled and allowed to air dry under cover for three days prior to kiln drying. Winandy, *et al.*, (1983) have concluded that a time delay between CCA treatment and kiln drying has little effect on strength losses.

Kiln drying was done in separate charges for the CCA-treated group and the water-treated group, but the same kiln schedule was used for both treatment groups. The kiln schedule used was as follows; 71 °C DBT and 60 °C WBT for 75 h, an air speed of 3 m s^{-1} with fan reversal every 3 h. Each kiln charge had a restraining load over the stock of 1460 kg during drying.

Conditioning and strength testing of samples were carried out as described in Sections 3.5 and 3.6.1, respectively. Preservative retentions of specimens were determined by X-ray fluorescence analysis as described in Section 3.7.2.

7.3 Results and discussion

Average treatment retentions for the CCA-treated air dried and kiln dried timber samples were 13.5 kg m^{-3} and 13.2 kg m^{-3}, respectively. The average MC of the timber samples at the time of strength testing were 11.5% for the untreated control, 11.0% for the water-treated and kiln dried samples, 14.4% for the CCA-treated and air dried samples, and 11.8% for the CCA-treated and kiln dried samples.

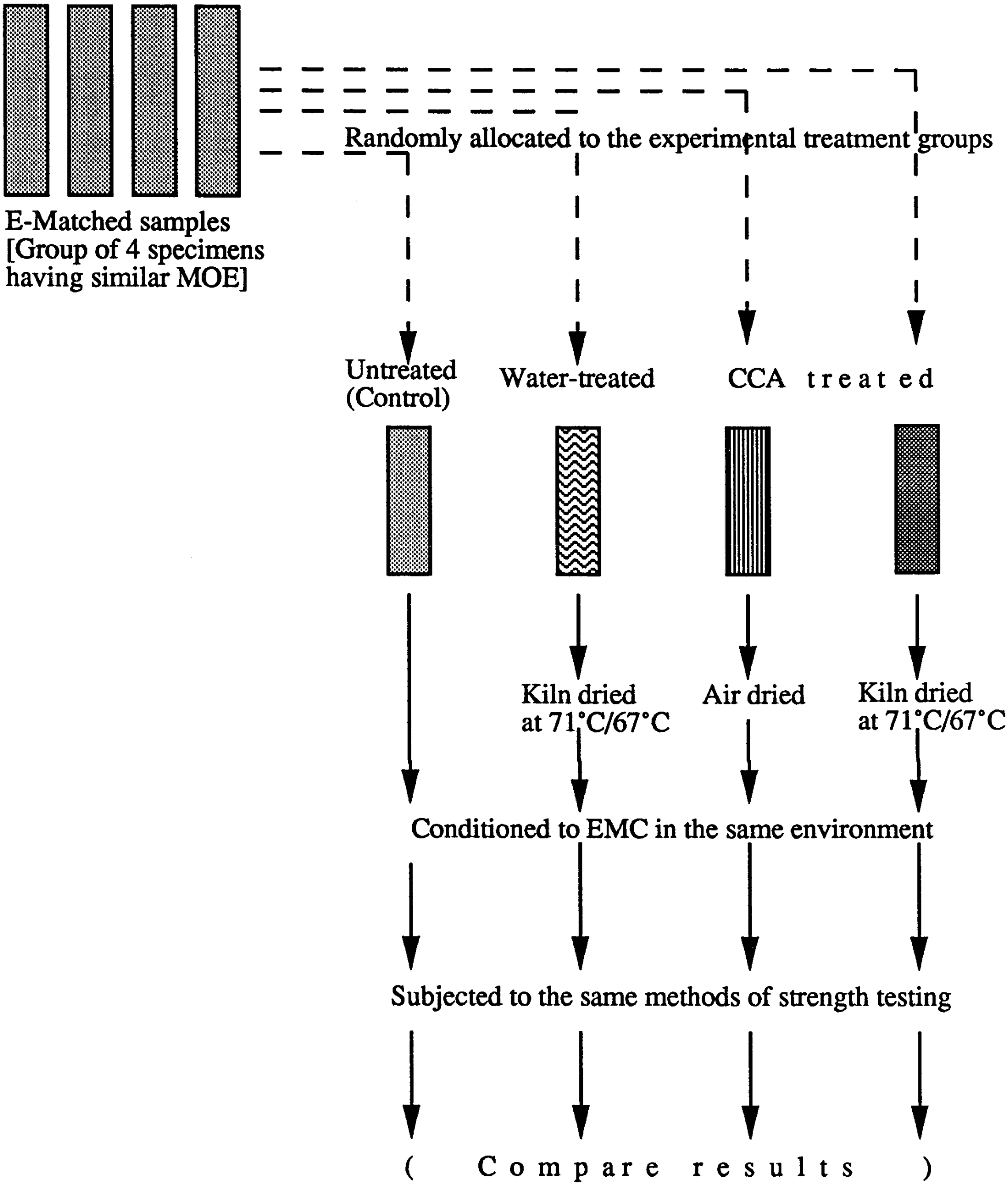


Figure 7.1 The design of the experiment to evaluate the effect of CCA treatment and re-drying at low temperature on the MOE and MOR of structural size timber

The MC for the CCA-treated and air dried samples was higher than for the other treatment groups. This is similar to the result observed with small clear-wood specimens (Section 4.1.3). Winandy (1989) also observed increased moisture contents in air dried CCA-treated structural size timber. He attributed this to the hydrophilic nature of CCA and a lack of enough thermal energy during drying to degrade the more hydrophilic hemicellulosic cell wall constituents.

7.3.1 Mechanical properties

The mean MOE and MOR, standard deviations and losses in these properties for the four treatment groups are summarized in Table 7.1. The effect of CCA treatment and LTD (71 °C) on MOE and MOR are also shown graphically in Figures 7.2a and 7.2b, respectively, to enable the effect of treatment on strength to be compared more easily. 95% confidence interval are also included on the graphs to indicate the range of values within which the mean lies.

MOE generally increased after treatment and re-drying. The water-treated timber showed a significant ($p < 0.05$) increase in MOE of 5.2% after kiln drying. This increase may have been influenced, in part, by the lower EMC of the water-treated samples during testing. However, the difference in MC between the water-treated and untreated controls was statistically insignificant ($p > 0.05$). When air dried after CCA treatment MOE increased significantly ($p < 0.05$) by 11.7% but after kiln drying CCA-treated samples showed a small statistically insignificant ($p > 0.05$) decrease in MOE.

The MOR in all treated groups increased after treatment and LTD. MOR increased by 16.0%, 27.6% and 0.3% in the water-treated and kiln dried, CCA-treated and air dried, and in the CCA-treated and kiln dried groups, respectively. The latter increase in MOR for the CCA-treated and kiln dried group was statistically insignificant ($p > 0.05$). The increase in MOR of CCA-treated air dried samples is generally constistent with the results of tests on CCA-treated, air dried small clear-wood specimens (see Table 7.2).

Table 7.1 The effect of CCA treatment and re-drying at low temperature on the MOE and MOR of structural size radiata pine timber.

Property	Treatment Group	EMC (%) a	Strength Property Mean (MPa) b	Strength change (%)	Paired t-value (2-tail) c
MOE	Control	11.5	9954.5 (1639.0)		
	Water-treated & Kiln dried	11.0	10468.7 (1645.7)	+5.2	-4.326 ** (0.0001)
	CCA-treated & Air dried	14.4 (13.5)	11117.7 (1601.0)	+11.7	-9.668 ** (0.0001)
	CCA-treated & Kiln dried	11.9 (13.2)	9954.2 (1698.0)	-0.003	0.002 + (0.9983)
MOR	Control	11.5	33.7 (11.7)		
	Water-treated & Kiln dried	11.0	39.1 (13.1)	+16.0	-2.877 * (0.0057)
	CCA-treated & Air dried	14.4 (13.5)	43.0 (14.1)	+27.6	-4.427 ** (0.0001)
	CCA-treated & Kiln dried	11.9 (13.2)	33.8 (12.3)	+0.3	-0.060 + (0.9521)

a, b, c Numbers in parenthesis refer to the treatment retention (in kg m^{-3}), standard deviation and significant probability, respectively.

* Significant at 95% confidence level

** Highly significant

\+ Not significant at 95% confidence level

Table 7.2 Change in MOR of small clear-wood specimens and structural size radiata pine timber after CCA treatment and re-drying at low temperature.

Specimen type	Treatment group	Retention (kg m^{-3})	MOR (MPa) a	Strength loss (%)
Small clear-wood	CCA-treated High-R/air dried	37.5	70.6 (61.36)	+15.0*
	CCA-treated Low-R/air dried	13.1	74.6 (77.22)	-3.4+
Structural size	CCA-treated Low R/air dried	13.5	43.0 (33.70)	+27.6*
	CCA-treated Low R/kiln dried	13.2	33.8 (33.70)	+0.3+

a Numbers in parenthesis refers to the MOR of the corresponding control.

* Significant at 95% level

\+ Not significant at 95% level

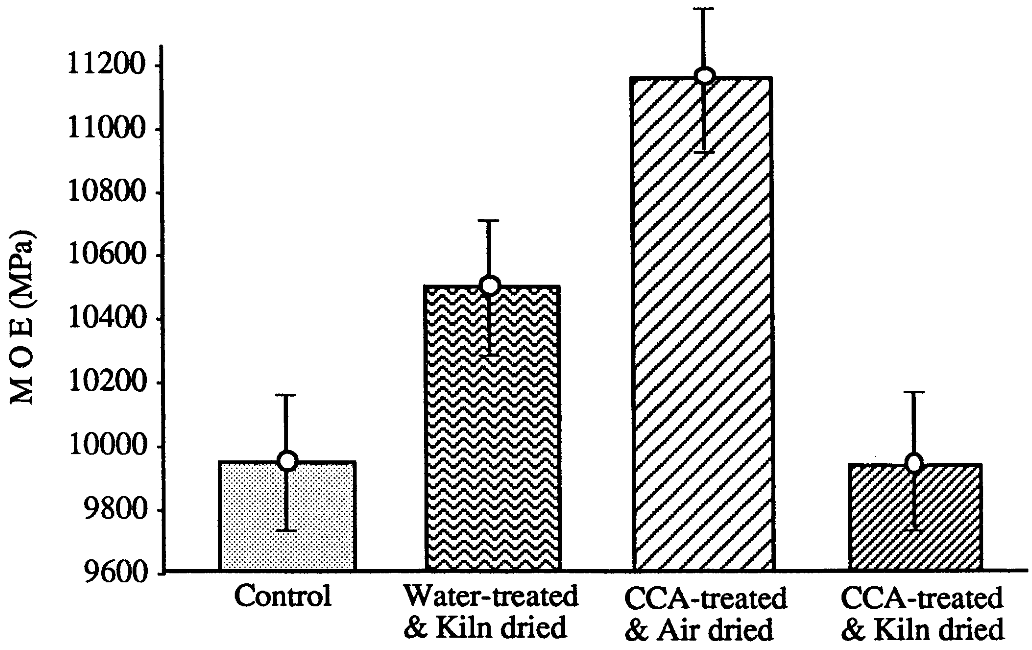


Figure 7.2a The mean MOE of structural size timber after CCA treatment and re-drying at low temperature

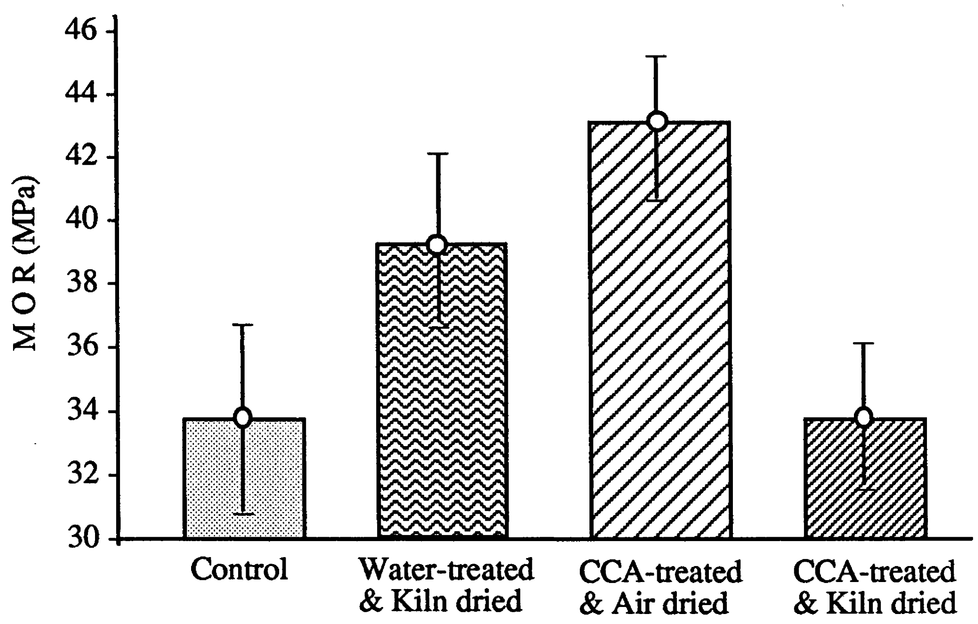


Figure 7.2b The mean MOR of structural size timber after CCA treatment and re-drying at low temperature

The increases in MOR after treatment (including water treatment) and LTD (including air drying) are in accord with previous findings. Winandy and Boone (1988) found significant increases in the MOR of SRSS grade 50 x 150 mm southern pine structural size timber after CCA treatment and LTD. MOR increased by 10% for samples treated to 6.4 kg m^{-3} and dried by LTD (71 °C) and for samples treated to 9.6 kg m^{-3} and air dried. When dried at 71 °C, the samples treated to 9.6 kg m^{-3} increased in MOR by 17%. The water-treated samples also showed an increase in MOR by 15% after LTD (71 °C). Winandy and Boone, (1988) suggested that strength increases in their timber after CCA or water treatment and air drying may have been associated with the presence of pith. Pith was largely absent from the radiata pine tested here, so other factors may be responsible for the strength increases.

Increases in MOR of SR2 grade 50 x 150 mm southern pine timber after CCA treatment and air drying were also observed by Winandy and Boone (1988). Lee (1985) found insignificant reductions in MOR for southern pine structural timber after CCA treatment (R = 9.6 kg m^{-3}) and air drying. However, Winandy (1989) found a 7 to 13% reduction in MOR of structural southern pine timber after CCA treatment (R = 9.6 kg m^{-3}) and air drying. The reasons for these discrepancies are not known.

7.3.2 **Percentile distribution**

The percentile distribution for MOE and MOR are shown graphically in Figures 7.3a and 7.3b. These graphs show how the various treatment groups compare with the controls across the distribution. Percentile estimates of MOE and MOR at selected points across the distribution are also presented in Table 7.3.

The effect of CCA treatment and re-drying at low temperature (LTD) on the strength losses or gains across the percentile distribution are presented in Table 7.3 (i. e., numbers in parenthesis). MOE and MOR of the CCA-treated air dried timber samples increased by 10.8% to 16.9% and 23.7% to 37.5%, respectively, from the 5th to 75th percentile of the strength distribution. The MOE of the CCA treated kiln dried samples decreased by 1.3% and 3.8% at the 5th and 10th percentiles, respectively, but increased from the 25th to 75th percentile by 0.6% to 4.1%. The MOR of the CCA treated kiln dried samples decreased by 5.7% at the 5th percentile, but increased by 1.4% to 3.6% at the 10th to 50th percentile and then decreased by 1.1% at the 75th percentile. Whether these strength losses or gains are statistically significant is not known since there is no valid statistical test of significance for percentile distributions [Barnes and Mitchell, 1984].

Table 7.3 The MOE and MOR (in MPa) of CCA-treated, low temperature dried structural size radiata pine timber at selected percentiles of the property distribution

Property	Treatment Group	Percentile				
		5th	10th	25th	50th	75th
MOE	Control	7258.3	7890.1	8563.7	9997.7	11006.3
	Water-treated & Kiln dried	7761.6 (+6.9)	8217.1 (+4.1)	9345.7 (+9.1)	10260.4 (+2.6)	11710.6 (+6.4)
	CCA-treated & Air dried	8484.0 (+16.9)	9023.4 (+14.4)	9876.8 (+15.3)	11076.7 (+10.8)	12211.8 (+10.9)
	CCA-treated & Kiln dried	7161.1 (-1.3)	7587.1 (-3.8)	8616.5 (+0.6)	10136.8 (+1.4)	11453.3 (+4.1)
MOR	Control	14.4	19.4	24.0	32.3	43.6
	Water-treated & Kiln dried	17.5 (+21.8)	24.0 (+23.2)	28.7 (+19.7)	36.8 (+13.7)	49.2 (+12.7)
	CCA-treated & Air dried	19.8 (+37.5)	24.1 (+23.7)	33.5 (+39.4)	41.8 (+29.1)	54.3 (+24.4)
	CCA-treated & Kiln dried	13.5 (-5.7)	20.1 (+3.6)	24.4 (+1.7)	32.8 (+1.4)	43.2 (-1.1)

Note: Numbers in parenthesis are percent strength changes based on the property value of the control group. Number preceded by a negative sign (-) indicate a loss in strength and those preceded by a positive sign (+) indicate a gain in strength.

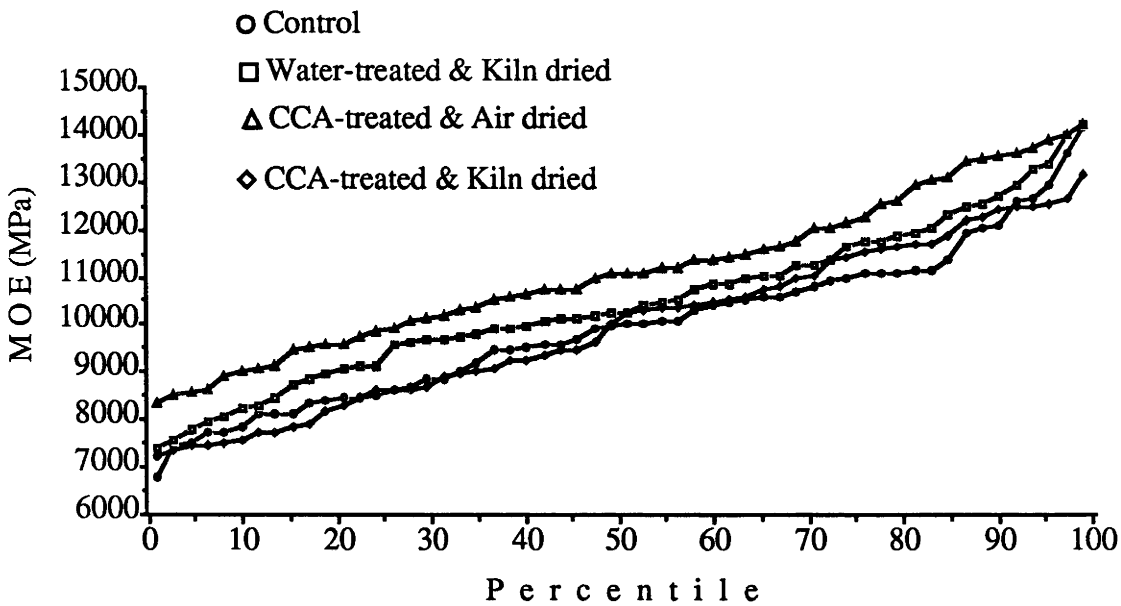


Figure 7.3a Cumulative percentile distribution of MOE for the three treated groups and the control group of structural size radiata pine timber dried at low temperature after treatment

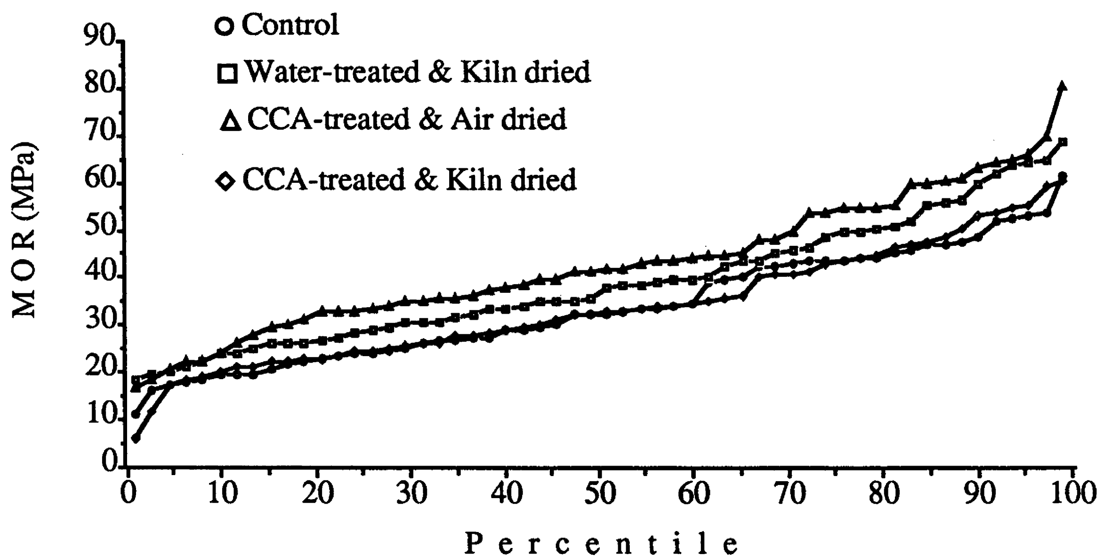


Figure 7.3b Cumulative percentile distribution of MOR for the three treated groups and the control group of structural size radiata pine timber dried at low temperature after treatment

It is apparent that CCA treatment up to 13.5 kg m^{-3} retention and LTD ($\leq$ 71°C) had little deleterious effect on the MOE and MOR of structural size radiata pine timber. Instead, it appears that CCA treatment and LTD improved MOE and MOR. This is in accord with earlier results based on mean property values (Section 7.3.1).

The MOE of CCA-treated timber showed small increases after air drying from 10.8% to 16.9% across the distribution. Similarly, the reductions (at the 5th and 10th percentile) and increases (at the 25th, 50th and 75th percentile) in MOE for the kiln dried CCA treated timber were also small.

The MOR of the CCA treated timber that was kiln dried decreased by 5.7% at the 5th percentile, increased from the 10th to the 50th percentile, and then decreased again at the 75th percentile. However all of the latter changes were insignificant. In contrast, the MOR of the CCA-treated timber that was air dried increased significantly from 23.7% to 39.4% across the strength distribution.

7.4 Conclusions

The MOE and MOR of structural size radiata pine timber was not significantly ($p > 0.05$) reduced by CCA treatment to a retention up to 13.5 kg m^{-3} and re-drying by air drying or LTD up to 71 °C. Generally there was an increase in the MOE and MOR after CCA treatment and re-drying at low temperature. This finding was consistent with results from tests on small clear-wood specimens.

The increases in MOE and MOR of the water treated kiln dried samples may have been influenced by the lower EMC of the samples compared to the untreated controls, but the latter cannot entirely explain the observed strength increases.

The results of the evaluation of percentile strength distributions support the findings based on the evaluation of the property means.

Chapter Eight

CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

The main aims of this study were to determine the effect of CCA treatment and re-drying on the mechanical properties of small clear-wood and structural size radiata pine timber and then to compare the strength losses in the two specimen types. The principal materials used were a CCA-Type C preservative and radiata pine timber stress graded to F5 in accord with AS 1748 - 1978. The mechanical properties evaluated were modulus of elasticity (MOE), modulus of rupture (MOR) and compression parallel to the grain or maximum crushing strength (MCS).

Results of the experiments were discussed in the preceding chapters (Chapters 4, 5, 6 and 7) and conclusions were then drawn. These results are summarized in this chapter and final conclusions are made. Finally, some suggestions for further research are made.

8.1 Summary of findings

8.1.1 Effect of CCA treatment and re-drying on the MOE, MOR, and MCS of small clear-wood specimens.

CCA treatment (R = up to 37.5 kg m^{-3}) and air drying increased the MOR of small clear-wood specimens by 15.0%. A reduction of 3.4% was observed in the MOR of specimens treated to a retention of 13.1 kg m^{-3} and then air dried. MCS showed a small, but statistically significant reduction of 5.6 to 7.0 % after CCA treatment and air drying.

Water treatment and re-drying by air or oven drying at 96.5 °C for 18 hours had no deleterious effect on the MOE, MOR and MCS of small clear-wood specimens. MOE was increased by 7.0% and 10.4% respectively after air and oven drying. MOR and MCS showed small decreases after water treatment and air and oven drying. Heat treatment (by oven drying) at 96.5 °C for 18 hours increased MOE, MOR and MCS by 6.4%, 10.4% and 10.6%, respectively.

Re-drying of CCA-treated specimens (R = 19.3 - 30.4 kg m^{-3}) at high temperature (116 °C) for 21 hours decreased MOR by 28.1% - 31.0%. The MCS of CCA-treated small clear-wood specimens increased by 8.9% - 9.8% after HTD. MOE was unaffected by CCA treatment and HTD. Treatment retention, either high (R = 30.4 kg m^{-3}) or low (R = 19.3 kg m^{-3}) had an insignificant effect on the mechanical properties of small clear-wood radiata pine specimens after HTD.

An examination of the effects of CCA treatment and re-drying using the percentile distribution of the mechanical properties gave similar findings to those obtained (above) when the average property values were used. However, when the percentile distribution data were used to calculate mechanical properties, higher strength losses or gains were obtained than when the average data were used. This effect was pronounced when results were compared at the 5th percentile.

8.1.2 Effect of CCA treatment and re-drying on the MOE and MOR of structural size timber

Re-drying of CCA-treated structural size radiata pine timber at low temperature (maximum 71 ° C) increased MOE and MOR by 11.7% and 27.6%, respectively. Water treated specimens also showed increases in MOE and MOR of 5.2 and 16.0%, respectively, after LTD. The reasons for the increases in MOE and MOR of the CCA treated and water-treated structural size radiata pine timber after LTD are unknown. Previous work on the effect of CCA treatment and LTD on the strength properties of southern pines also showed strength increases.

Re-drying of CCA-treated (R = 19.1 - 31.6 kg m^{-3}) structural sized radiata pine timber at high temperature (116 °C) reduced the MOR by 28.1% to 34.5% while MOE was unaffected. Treatment retention had little effect on the MOE and MOR of treated structural size timber after HTD. However, the presence of the CCA in wood helped in the occurrence of strength losses since strength losses of water treated specimens after HTD were considerably smaller than in CCA-treated specimens.

Evaluation of the effect of CCA treatment and re-drying using percentile distributions gave higher strength losses or gains than when the average data was used, particularly when results were compared at the 5th percentile.

8.1.3 Relationship between findings in small clear-wood specimens and in structural size radiata pine timber after CCA treatment and re-drying

The strength values obtained from testing small clear-wood specimens differed in magnitude from those obtained from testing structural size timber. The strength properties of the small clear-wood specimens were higher than the structural size timber indicating the deleterious effects of growth defects (present in structural size timber, but absent from small clear-wood specimens) have on strength. However, results for the small clear-wood specimens and the structural size timber showed some similarities. The relationship between tests undertaken on small clear-wood specimens and those undertaken on structural size timber after CCA treatment and re-drying may be viewed in terms of the relative strength losses or gains obtained after CCA treatment and re-drying (see Tables 6.2 and 7.2). Findings that are common to both specimen types are as follows;

(1) CCA treatment and air drying does not adversely affect the MOE and MOR of small clear-wood specimens and structural size timber.

(2) The MOR of CCA-treated small clear-wood specimens and structural size timber decreased after HTD, but MOE was unaffected. Treatment retentions had a negligible effect on the MOE and MOR of small clear-wood specimens and structural size timber after re-drying.

(3) CCA treatment and LTD (71 °C) had no deleterious effect on the MOE and MOR of small clear-wood specimens and structural size timber.

Apparently the CCA treatment and re-drying interacted with the common chemical constituents (i.e., the celluloses, hemicelluloses and lignin) present in both the small clear-wood specimens and structural size timber rather than with defects associated with the latter.

8.2 Final conclusions

The experiments described in the preceding chapters used small clear-wood specimens and structural size radiata pine timber of a single structural grade, obtained from one source (CSR, Tumut, N.S.W.) and only used a single type of CCA for the preservative treatment. Thus, the following conclusions may only apply to radiata pine from the parent population sampled, stress graded as F5 in accord with AS 1748 -1978, and only when treated with a CCA-Type C preservative. Nevertheless, the results of this study may have some implications for future research studies and also for the timber processing industry and for timber design authorities (Section 8.3). The final conclusions are as follows:

(1) CCA treatment and air drying has no deleterious effect on the MOE and MOR of radiata pine, but slightly reduces MCS.

(2) Treatment retention has little, if any, influence on the mechanical properties of radiata pine after HTD. However, the presence of CCA preservative in wood does help in the occurrence of strength losses since strength losses of water-treated specimens after HTD were lower than in CCA treated specimens.

(3) Re-drying treated radiata pine at low temperatures (≤ 71 °C DBT) may increase the mechanical properties of both small clear-wood specimens and structural size timber. Strength increases appear to be greater in the latter.

(4) Re-drying treated radiata pine using a HTD schedule up to 116 °C DBT/ 82 °C WBT has no deleterious effect on MOE and MCS, but significantly reduces MOR. The magnitude of the strength losses are greater when the data is examined at the 5th percentile of the property distribution.

(5) MOE and MOR of structural size timber increases after water treatment and LTD. The reasons for the increases in strength of both water and CCA-treated structural size radiata pine timber after drying at low temperature are not known.

(6) Test results obtained from testing small clear-wood specimens are useful in predicting the effect of CCA treatment and re-drying on the mechanical properties of structural size radiata pine timber.

8.3 Implications and recommendations

Air drying or conventional kiln drying (≤ 71 °C DBT) is suitable for the drying of CCA treated F5 structural size radiata pine timber. Strength properties may even increase as a result of CCA treatment and LTD. This finding is worthy of further research. This study showed that re-drying treated structural size radiata pine timber at 71 °C caused no loss in strength and therefore it is possible that higher temperatures (i.e., > 71 °C but < 116 °C) could be used for the drying of CCA-treated timber. Further studies should be carried out to determine the highest temperature at which CCA-treated F5 radiata pine can be dried without causing significant strength losses. This work should be undertaken with the aim of developing an effective kiln schedule for CCA-treated structural size timber. The development of kiln schedules for other grades and other important structural timber species should also be considered.

Re-drying of treated radiata pine at high temperature caused a significant decrease in MOR and therefore HTD should not be used to dry treated radiata pine timber even though HTD had an insignificant effect on MOE. The reduction in MOR due to CCA treatment and HTD was large enough to down-grade the material. MOR was reduced after CCA treatment and re-drying using HTD, but MOE was unaffected and therefore the use of mechanical stress grading for treated radiata pine using the current MOR/MOE regression values is probably inappropriate.

REFERENCES

American Society for Testing and Materials. (1980). Standard methods for testing small clear specimens of timber. *ASTM Standard D 143-52*. ASTM, Philadelphia, PA., USA.

American Society for Testing and Materials. (1980). Standard methods of static tests of timbers in structural sizes. *ASTM Standard D 198-76*. ASTM, Philadelphia, PA., USA.

American Society for Testing and Materials. (1980). Standard methods for establishing clear wood strength values. *ASTM Standard D 2555-78*. ASTM, Philadelphia, PA., USA.

American Society for Testing and Materials. (1980). Standard methods for evaluating allowable properties for grades of structural lumber. *ASTM Standard D 2915-74*. ASTM, Philadelphia, PA., USA.

Ashby, M.F. and Jones, D.R.H. (1986). Engineering Materials 2. pp 241 -263, Pergamon Press, Oxford.

Bariska, M., Pizzi, A. and Conradie, W.E. (1988). Structural weakening of CCA-treated timber. *Holzforschung* 42(5):339-345.

Barnes, H.M. and Mitchell, P.H. (1984). Effects of post-treatment drying schedule on the strength of CCA-treated southern pine dimension lumber. *Forest Products J.* 34(6): 29-33.

Barnes, H.M. (1985). Effect of steaming temperature and CCA retention on mechanical properties of southern pine. *Forest Products J.* 35(6): 31-32.

Barnes, H.M. (1986). Strength-drying relationships for CCA-treated wood. In: Hamel, M. P., ed. *Drying lumber for quality and profit.* Proceedings 47356. pp 42 - 49, Forest Prod. Res. Soc., Charlotte, North Carolina, .

Barnes, H.M. and Moore, S. (1987). Effect of post-treatment drying schedule on the modulus of elasticity of CCA-treated southern pine dimension stock using non-destructive methods. *The International Research Group on Wood Preservation.* Doc. No. IRG/WP/3413, 4 p.

Barnes, H.M., Winandy, J.E. and Mitchell, P.H. (1990). Effect of initial and post-treatment drying temperature on the bending properties of CCA-treated southern pine. *J. Inst. Wood Science.* 11(6): 222-230.

Beall, F.C. (1982). Effect of temperature on the structural uses of wood and wood products. In: Meyer, R. W. and R. M. Kellogg, editors. Structural Use of Wood in Adverse Environments. Van Nostrand Reinhold, New York. pp. 9-19.

Bendtsen, B.A., Gjovik, L.R. and Verrill, S.P. (1983). Mechanical properties of longleaf pine treated with waterborne salt preservatives. *USDA For. Serv. Res. Pap FPL 434,* Forest Products Laboratory, Madison, Wis., 16 p.

Bier, H. (1983). The strength properties of small clear specimens of New Zealand-grown timber. *FRI Bulletin No. 41,* Forest Research Institute, New Zealand Forest Service, Private bag, Rotorua, N.Z., 26 p.

Bodig, J. (1982). Moisture effects on structural use of wood. In: Meyer, R.W. and Kellogg, R.M., editors.Structural Use of Wood in Adverse Environments. Van Nostrand Reinhold, New York, pp. 53-75.

Boggio, K. and Gertjejansen, R. (1982). Influence of ACA and CCA waterborne preservatives on the properties of aspen waferboard. *Forest Products J.* 32(3): 22-26.

Bolden, S.A. (1991). In-grade testing: Implication for Australian radiata pine. A discussion paper, In-grade testing seminar, Radiata Pine Association of Australia Inc., NSW, Australia, 25 p.

*

Brown, H.P., Panshin, A.J. and Forsaith, C.C. (1952). Textbook of Wood Technology. Vol. 2, 1st. ed., McGraw-Hill Book Co., New York, 783 p.

Browning, B.L. (1963). The composition and chemical reactions of wood. In: Browning, B.L. editor The Chemistry of Wood, pp. 57-101, Interscience Publishers, John Wiley & Sons, New York. .

Connell, M. and Nicholson, J. (1990). A review of 55 years usage of CCA and CCA-treated timber. Koppers-Hickson Timber Protection Pty Ltd. NSW, 9 p.

Desch, H.E. and Dinwoodie, J.M. (1981). Timber: Its Structure, Properties and Utilisation. 6th. edn. The Macmillan Press Ltd., London. 410 p.

Donnelly, D.J. and Siemon, G.R. (1989). Effect of sapstaining and CCA treatment on strength properties of radiata pine poles. *W.U.R.C. Technical Report.* Department of Conservation and Land Management, Weir Road Harvey, WA, 6 p.

Erickson, H.D. and Reese, L.W. (1940). The effect of several chemicals on the swelling and crushing strength of wood. *J. Agric. Res.* 60 (9):593-603.

Evans, P.D., Beutel, P., Hoggett, A.J. and Stodart, D.M. (1991). The impact bending strength of slash pine after preservative treatment. *Holz als Roh- und Werkstoff* 49 (7/8):.270.

Gerhards, C.C. (1968). Seasoning factors for modulus of elasticity and modulus of rupture. *Forest Products J.* 18(11): 27-35.

Gerhards, C.C. (1979). Effect of high-temperature drying on tensile strength of Douglas-fir 2 by 4's. *Forest Products J.* 29(3): 39-46.

*Bootle, K.R. (1983). Wood in Australia. Types Properties and Uses. McGraw-Hill, Sydney, 443p.

Gerhards, C.C. (1982). Effect of moisture content and temperature on the mechanical properties of wood: an analysis of immediate effects. *Wood and Fiber* 14(1): 4-36.

Haygreen, J.G. and Bowyer, J.L. (1982). Forest Products and Wood Science: An introduction. pp 219 - 249, The Iowa State University Press, Ames, Iowa.

Hillis, W.E. (1984). High temperature and chemical effects on wood stability. Part 1: General considerations. *Wood Science and Technology* 18 (4): 281-293.

Huffman, D.R. (1977). High-temperature drying effect on the bending strength of spruce-pine-fir joists. *Forest Products J.* 27(3): 55-57.

Kass, A.J., Wangaard, F.F. and Schroeder, H.A. (1970). Chemical degradation of wood: The relationship between strength retention and pentosan contents. *Wood and Fiber* 3(1):31-39.

Kininmonth, J.A. (1958). The drying of radiata pine sawn timber pressure treated with waterborne preservatives. *N. Z. Forest Service Tech. Paper No. 26.* New Zealand Forest Service, 32 p.

Kininmonth, J.A. and Williams, D.H. (1974). Kiln schedules for New Zealand timbers. *Paper 13: Timber drying in New Zealand,* F.R.I. Symposium No. 17, pp 107-119, Forest Research Institute, Rotorua.

Kininmonth, J.A. and Whitehouse, L.J. (1991). Properties and Uses of New Zealand Radiata Pine, Volume 1 - Wood Properties, Ministry of Forestry, FRI, Rotorua, N.Z., 216 p.

Knuffel, W.E. (1985). The effect of CCA preservative treatment on the compression strength of South African pine structural timber. *Holzforschung und Holzverwertung* 37(5): 96-99.

Koch, P. (1971). Process for straightening and drying southern pine 2 by 4's in 24 hours. *Forest Products J.* 21(5):17-24.

Kozlik, C.J. (1976). Kiln temperature effect on tensile strength of Douglas-fir and western hemlock lumber. *Forest Products J.* 26(10): 30-34.

Kozlik, C.J. (1982). Kiln-drying douglas-fir pole sections: Effect on strength and checking. *Forest Products J.* 32(6): 24-30.

Lee, A.W.C. (1985). Effect of CCA-treating and air-drying on the properties of southern pine lumber and plywood. *Wood and Fiber Science.* 17(2): 209-213.

LeVan, S.L. and Winandy, J.E. (1990). Effects of fire-retardant treatments on wood strength: A review. *Wood and Fiber Science.* 22(1): 113-131.

Lew, J.D. and Dost, W.A. (1983). Hardness of Douglas-fir and ponderosa pine treated with ACA, CCA and penta-petroleum. *Forest Products J.* 33(7/8): 17-18.

Mackay, J.F.G. (1973). Surface checking and drying behavior of *Pinus radiata* sapwood boards treated with CCA preservative. *Forest Products J.* 23(9): 92-97.

Madsen, B. and Eng, P. (1984). Moisture content effects in timber. *Proceedings of the Pacific Timber Engineering Conference*, Paper 144B, pp 786 - 790, University of Auckland, N.Z.

Mitchell, P.H. and Barnes, H.M. (1986). Effect of drying temperature on the clear wood strength of southern pine treated with CCA-type A preservative. *Forest Products J.* 36(3): 8-12.

Mottet, A.L. (1982). Adverse effects of processing environments on working stresses. In: Meyer, R. W.; Kellogg, R. M. editors. Structural Use of Wood in Adverse Environments, pp. 398-414, Van Nostrand Reinhold, New York.

Panshin, A.J. and De Zeeuw, C. (1980). Textbook of Wood Technology : Structure, Identification, Properties and Uses of the Commercial Woods of the United States and Canada, 4th ed. McGraw-Hill, New York. 722 p.

Price, E.W. and Koch, P. (1980). Kiln time and temperature affect shrinkage, warp, and mechanical properties of southern pine lumber. *Forest Products J.* 30(8): 41-47.

Salamon, M. (1969). High-temperature drying and its effect on wood properties. *Forest Products J.* 19(3): 27-34.

Siemon, G.R. (1979). Effect of CCA preservative treatment on bending strength of small clear specimens of high-temperature-dried and air-dried caribbean pine. *Proceedings of the 19th Forest Products Research Conference.* November 12-16, CSIRO Div. of Building Research, Melbourne, 4 p.

Skaar, C. (1972). Water in Wood. Syracuse Univ. Press, Syracuse, N.Y. 218 p.

Skaar, C. (1988). Wood-Water Relations. Springer-Verlag, New York, 283 p.

Snedecor, G.W. and Cochran, W.G. (1967). Statistical Methods. The Iowa State Univ. Press, Ames, Iowa, USA. 593 p.

Stamm, A.J. (1964). Wood and Cellulose Science. Ronald Press Co., New York. 549 p.

Standard Association of Australia. (1964). Australian Standard Glossary of Terms Used in Timber Standards. *Australian Standard 01 - 1964,* SAA, North Sydney, NSW, 47 p.

Standard Association of Australia. (1978). Mechanically stress-graded timber and rules for mechanical stress grading of timber. *Australian Standard 1748 and 1749-1978.* SAA, North Sydney, NSW, 20 p.

Standard Association of Australia. (1979). Timber framing code: code of practice for construction in timber framing.*Australian Standard 1684-1979.* SAA, North Sydney, NSW, 56 p.

Standard Association of Australia. (1980). Preservative treatment for sawn timber, veneer and plywood. *Australian Standard 1604-1980.* SAA, North Sydney, NSW, 22 p.

Standard Association of Australia. (1986). Timber--Softwood: Visually stress-graded for structural purposes. *Australian Standard 2858-1986.* SAA, North Sydney, NSW, 34 p.

Standard Association of Australia. (1988). Timber structures code. *Australian Standard 1720.1-1988.* SAA, North Sydney, NSW, 85 p.

Thompson, W.S. (1969a). Effect of steaming and kiln drying on the properties of southern pine poles. Part1: Mechanical properties. *Forest Products J.* 19(1): 21-28.

Thompson, W.S. (1969b). Effects of chemicals, chemical atmospheres, and contact with metals on southern pine wood: *A review: Research Report No. 6.* Forest Products Utilization Laboratory, Mississippi State University, Mississippi, 33 p.

Thompson, W.S. (1982). Adverse environments and related design considerations--chemical effects. In: Meyer, R. W.; Kellogg, R. M. editors. Structural Use of Wood in Adverse Environments, pp 117-129, Van Nostrand Reinhold, New York.

U.S. Forest Products Laboratory. (1974). Wood Handbook: Wood as an Engineering Material. *USDA Agr. Handb. 72* (rev.). Madison, WI 53705, 413 p.

Van Vlack, L.H. (1967). Elements of Material Science. 2nd. ed.pp 375 - 392, Addison-Wesley Publishing Co. Inc., Sydney.

Walker, H.M. and Lev, J. (1958). Elementary Statistical Methods. Henry Holt and Company, New York, 302 p.

Wangaard, F.F. (1966). Resistance of wood to chemical degradation. *Forest Products J.* 16(2):53-64.

Wazny, J. and Krajewski, K.J. (1992). Long-term effect of CCA and NaPCP preservatives on the compression strength of radiata pine sapwood. *Holzforschung* 46(6):533-535.

Williams, D.H. (1974). Drying of pressure treated radiata pine sawn timber. *Paper 15: Timber Drying in New Zealand,* F.R.I. Symposium No. 17, pp 135 - 154, Forest Research Institute, Rotorua.

Winandy, J.E., Bendtsen, B.A. and Boone, R.S. (1983). Effect of delay between treatment and drying on the toughness of CCA-treated southern pine. *Forest Products J.* 33(6): 53-58.

Winandy, J.E., Boone, R.S. and Bendtsen, B.A. (1985). Interaction of CCA preservative treatment and redrying: Effect on the mechanical properties of southern pine. *Forest Products J.* 35(10): 62-68.

Winandy, J.E. (1988). Effects of treatment and redrying on mechanical properties of wood. In: Hamel, M., editor. *Proceedings 47358; Wood protection techniques and the use of treated wood in construction,* pp 54 - 62, Oct. 28 - 30, Memphis, TN. Madison, WI. Forest Products Research Society.

Winandy, J.E. and Boone, R.S. (1988). The effect of CCA preservative treatment and redrying on the bending properties of 2 x 6 southern pine lumber. *Wood and Fiber Science.* 20(3): 350-364.

Winandy, J.E. (1989). CCA preservative treatment and redrying effects on the bending properties of 2 x 4 southern pine. *Forest Products J.* 39(9): 14-21.

Wood, M.W., Kelso, W.C., Jr., Barnes, H.M. and Parikh, S. (1980). Effects of the MSU process and high preservative retentions on southern pine treated with CCA-type C. *Proceedings American Wood Preservers' Association.76,* pp 22-37.

Yao, J. and Taylor, F. (1979). Effect of high-temperature drying on the strength of southern pine dimension lumber. *Forest Products J.* 29(8): 49-51.

APPENDIX A

Definition of terms

Anisotropic - exhibiting different properties when tested along axes in different directions [Panshin & de Zeeuw, 1980].

Box-piling - a method of flat stacking timber for air drying or kiln drying in which the pieces of timber are 'stickered' layer by layer to produce square-end piles or unit package.

Bound water - water that is associated with the cell-wall substance of the wood.

Brash failure - failure of timber under static bending in which the fractured surface is characterized by a complete break with very little splintering (if any), indicating an abrupt mode of failure usually under small loads and deformations.

Check - ruptures along the grain that develop during seasoning either because of a difference in radial and tangential shrinkage or because of uneven shrinkage of the tissue in adjacent portions of the wood [Panshin & de Zeeuw,1980]

Clear-wood - wood free from all visible defects and imperfections.

Compression parallel to the grain - imposition of a compressive stress on wood by forces applied in a direction parallel to the grain [AS 01-1964].

Crushing - used to described compression failure when the plane of rupture is approximately horizontal [ASTM D 143 - 52].

Equilibrium moisture content - the moisture content at which wood neither gains nor loses moisture when subject to given conditions of humidity and temperature [AS 01-1964].

Fiber saturation point - a hypothetical point when all water is evaporated from the cell cavities, but the cell walls are still fully saturated with moisture. Fiber saturation point varies considerably between species but for practical purposes is usually assumed to be 28 - 30% MC.

Flat-sawn - cut so that the wide face of the piece is a tangential plane to the growth rings; timber in which the average inclination of the growth rings to the wide face is not more than 45 degrees [Wallis, 1970].

Full-cell process - process for impregnating wood with preservatives or chemicals in which a vacuum is drawn to remove air from the wood before admitting the preservative. This favours high level of adsorption and retention of preservative in the treated portions [USFPL,1974].

Growth rings - ring of wood on a transverse surface or in a cross-section, resulting from periodic growth of the tree [Panshin & de Zeeuw, 1980].

Hardwood - a conventional term used to denote the timber of broad leaved trees belonging to the botanical group Angiosperms [Wallis, 1970].

Heart-in-material - generally lower density material containing growth rings of radius less than 50 mm, that is, material at or close to the pith [AS 2858-1986].

Hemicellulose - group of carbohydrates found in the cell wall in more or less intimate association with cellulose; sometimes defined as those less-resistant substances in the cell wall which though insoluble in hot water can be removed with either hot or cold dilute alkalies or readily hydrolyzed into sugars and constituent acids by means of hot dilute acids [Panshin & de Zeeuw, 1980].

Hydrolysis - a chemical process of decomposition involving addition of water; the presence of dilute acids, enzymes, or other agents may be needed to induce the reaction [Panshin & de Zeeuw, 1980].

Hydroxyl group - refers to the OH groups which exist throughout the cellulosic and hemicellulosic portions of the wood cell-walls, serve as water sorption sites, and are believed to be responsible for the hygroscopicity of the wood [Skaar, 1972].

Hygroscopicity - the property of a substance, such as wood, which permits it to absorb and lose moisture readily.

Knot-area-ratio - the ratio of the projected cross-sectional area of one or more knots to the cross-sectional area of the piece [AS 2858-1986].

Kiln - a chamber used for drying timber, and in which the temperature and humidity of the circulating air can be suitably controlled [AS 01-1964].

Microfibril - bundle of cellulose polymer chains and associated polysaccharides of other types that are united at some regions in highly ordered crystalline lattices known as crystallites and are less highly ordered in the zones between the crystallites, or so called amorphous regions [Panshin & de Zeeuw, 1980]..

Maximum crushing strength - a measure of the maximum resistance to crushing that the wood offers in resisting a force acting parallel to the grain (e.g., the strength of timber as column)[Brown, *et al.*, 1952].

Modulus of elasticity - a measure of stiffness of the wood under bending loads; the ratio of the unit stress (below the elastic limit of the material) to the unit deformation [Brown, *et al.*, 1952].

Modulus of rupture - a measure of the maximum strength of the wood in bending [Brown, *et al.*, 1952]

Moisture content - the amount of water contained in the wood, usually expressed as a percentage of the weight of the ovendry wood [USFPL, 1974].

Moisture gradient - the difference in moisture content between layers or zones in a piece of timber [AS 01-1964].

Preservative - any substance that, for a reasonable length of time, is effective in preventing the development and action of wood-rotting fungi, borers of various kinds, and harmful insects that deteriorate wood [USFPL, 1974].

Quarter-sawn - timber in which the average inclination of the growth rings to the wide face is not less than 45 degrees [Wallis, 1970].

Relative humidity - ratio of the amount of water vapor present in the air to that which the air would hold at saturation at the same temperature. It is usually considered on the basis of the weight of the vapor but, for accuracy, should be considered on the basis of vapor pressures [USFPL, 1974].

Retention - the amount of preservative in the form of liquid or dry compound remaining in the timber after treatment [AS 01 - 1964].

Seasoning - process of removing moisture (drying) from wet wood, ideally to a moisture range appropriate to the conditions and purposes for which the timber is to be used, to improve its serviceability.

Shearing - used to described compression failure when the plane of rupture makes an angle of more than 45 degrees with the edge of the specimen.

Shrinkage - the reduction in dimension or volume of timber which takes place when the moisture content decreases below the fiber saturation point of the wood.

Softwood - a conventional term used to denote the timber of trees belonging to the botanical group Gymnosperms. Commercial timbers of this group are practically confined to the class Coniferae or the conifers [Wallis, 1970].

Stress grade - the classification of timber for structural purposes, indicating primarily its basic working stress in bending and, by implication, the basic working stresses for other mechanical properties. For example, a timber of stress grade F5, indicates that the particular material has a basic working stress in bending of approximately 5 to 5.5 MPa [AS 2858 - 1986].

Structural timber - timber to be used in construction and graded upon the strength of the piece and the use of the entire piece; timber for applications where strength is the essential element in its selection and use [Wallis, 1970].

APPENDIX B

Requirements for Penetration and Retention of General Purpose Preservatives
[An extract from AS 1604 - 1980,.Table 2]

REQUIREMENTS FOR PENETRATION AND RETENTION OF GENERAL PURPOSE PRESERVATIVES

Service conditions	Examples		Hazard (note 1)	Penetration requirement (note 2)	Minimum charge retention (notes 3 and 8), kg of preservative per cubic metre of wood									
					Creosote (note 4)	Pentachlorophenol (note 7)	Boliden K33	Celcure A Celcure A(P) Copas L.C.	SARMIX 3 Tanalith C	Tanalith CA	Tanalith NCA Celcure AN	Tanalith F Tanalith FXP	Celcure Z Tanalith Z and Boron Compounds (Boron calculated as H_3BO_3)	Permanite X
SPECIAL OR LIMITED (for use only where protection against insect attack is required	Lyctus immunization of timber, veneer and plywood; special plywood treatments against insects ONLY	1 2 3	See Table 3, as these are not general purpose treatments											
INDOORS ABOVE GROUND (for uses where greater protection than for Hazard 1 is required or where a decay hazard exists)	Framing, flooring, trim, lining, and plywood used in damp interior situations or where in danger from insect attack	4	Hazards where there is nil–slight leaching, but where decay and termite attack may occur	A (1, 2, 3) B (4) D (4, 3) F (1, 2)	96	4.8	3.5	5.3	5.6	4.2	3.7	5.6	8.0	8
OUTDOORS ABOVE GROUND	*Kept well painted* Weatherboards, window joinery; plywood in caravans, boats	4	Moderate (note 5)	A (1, 2, 3) B (4) D (4, 3)	96	4.8	3.5	5.3	5.6	4.2	3.7		(Celcure Z Tanalith Z only) 8	8
		5	Severe (note 5) or Tropical	A (1, 2) B (3, 4) D (all timbers)	128	6.4	6.4	8	8	8	6.9			12
	Unpainted as above and fence palings and rails, exposed decking, wet factories, greenhouses	5	Moderate (note 5)	A (1, 2) B (3, 4) D (all timbers)	128	6.4	6.4	8	8	8	6.9			12
		6	Severe or Tropical (note 5) (including green-houses, wet factories)	A (1, 2) C (3, 4) E (all timbers)	160	8	9.6	12.0	12	12	10.3			
GROUND CONTACT	Fence posts and plinths, timber in retaining walls	6	Moderate (note 5)	A (1, 2) C (3, 4) E (all timbers)	160	8	9.6	12	12	12	10.3			
		7	Severe or Tropical (note 5) (or where very long life is required e.g. house stumps)	A (1) C (2, 3, 4) E (all timbers)	240	12	16.0	20.0	20	20	17.3			
COOLING TOWERS	Structural timbers over 37 mm thick	6	All Hazards	A (1, 2) C (3, 4)	160	8	9.6	12	12	12	10.3			
	Slats and supports up to 37 mm thick (coniferous timbers only)	8	Severe (note 5) (due to small size and soft rot hazard)	B (all timbers)	240	12	24	24	24	24	24			
MARINE BORERS	Boat planking, plywood sheathing timber in estuarine or sea water	9	All Hazards	C (all timbers) E (all timbers)	320	-	32 (note 6)	32 (note 6)	32 (note 6)	32 (note 6)	32 (note 6)			

NOTES:
1. Treatment for a higher numerical hazard satisfies all requirements for a lower hazard.
2. The required pattern of penetration is indicated by a capital letter (A, B, etc) and is fully described in Table 1. Numbers in brackets refer to the natural durability of untreated heartwood (see Appendix D).
3. Retention is based on penetrated volume for sawn timber and on total volume for plywood and veneer and is calculated as kg of commercial preservative (oil, dry salt or paste) per cubic metre of wood.
4. For some purposes these preservatives cannot be recommended because of odour, colour or tendency to bleed, or because they cause painting difficulties.
5. Moderate hazards are typical of those in Australian southern capital cities. Severe hazards refer to unusually wet or tropical conditions where the risk of decay is considerably higher.
6. In tropical waters recommended only for coniferous timbers.
7. All in Paragraph A4 in Appendix A.
8. Increase the specified retentions by 20 percent in the case of eucalypt timber expected to be exposed to a severe hazard such as soft rot.

This is an extract <u>from AS 1604</u>. Use, out of context, could result in misinterpretation. Consult the Standard when using it in practice.

APPENDIX C

Types of CCA Preservatives

[An extract from AS 1604 - 1980, Table A2]

TYPES OF CCA PRESERVATIVES

[An extract from AS 1604 - 1980, Table A2]

Preservative	Composition (percent)		Elemental content (percent)	
Boliden K 33	Copper oxide (CuO)	14.8	Cu	11.82
(CCA-B under AWPA	Chromium trioxide (CrO_3)	26.6	Cr	13.83
standard)	Arsenic pentoxide (As_2O_5)	34.0	As	22.17
	Water	24.6		
Celcure A (dry salt)	Copper sulphate ($CuSO_4.5H_2O$)	32.0	Cu	8.14
	Potassium dichromate ($K_2Cr_2O_7$)	40.0	Cr	14.14
Copas LC (slurry)	Arsenic pentoxide ($As_2O_5.2H_2O$)	21.0	As	11.84
	Sodium pyroarsenate ($Na_4As_2O_7$)	7.0	As	2.96
Celcure A (P) (paste)	Copper sulphate ($CuSO_4.5H_2O$)	23.2	Cu	5.90
	Copper oxide (CuO)	2.8	Cu	2.24
	Sodium dichromate($Na_2Cr_2O_7.2H_2O$)	40.0	Cr	13.96
	Arsenic pentoxide ($As_2O_5.2H_2O$)	26.5	As	14.94
Celcure AN	Copper sulphate ($CuSO_4$)	30.0	Cu	11.94
	Sodium dichromate ($Na_2Cr_2O_7$)	32.0	Cr	12.70
	Arsenic pentoxide ($As_2O_5.2H_2O$)	28.5	As	16.08
	Sodium pyroarsenate ($Na_4As_2O_7$)	9.5	As	4.03
Sarmix 3	Copper sulphate ($CuSO_4,5H_2O$)	35.0	Cu	8.91
Tanalith C (dry salt) or	Potassium dichromate ($K_2Cr_2O_7$)	45.0	Cr	15.91
Tanalith C (P) (slurry)	Arsenic pentoxide ($As_2O_5.2H_2O$)	20.0	As	11.27
(CCA-C under AWPA				
standard)				
Tanalith CA (dry salt)	Copper sulphate ($CuSO_4$)	22.4	Cu	8.92
or	Sodium dichromate ($Na_2Cr_2O_7$)	39.0	Cr	15.48
Tanalith CA(P) (slurry)	Arsenic pentoxide ($As_2O_5.2H_2O$)	33.4	As	14.82
	Sodium pyroarsenate ($Na_4As_2O_7$)	5.2	As	2.16
Tanalith NCA (dry salt)	Copper sulphate ($CuSO_4$)	29.7	Cu	11.82
or	Sodium dichromate ($Na_2Cr_2O_7$)	31.7	Cr	12`.58
Tanalith NCA(P) (slurry)	Arsenic pentoxide ($As_2O_5.2H_2O$)	26.3	As	18.82
	Sodium pyroarsenate ($Na_4As_2O_7$)	12.3	As	5.20

APPENDIX D

Tables of analysis of variance (ANOVA), means, standard deviations, standard errors, and comparison of means for data in Chapters 4, 5, 6, and 7.

ANOVA, means, standard deviation, standard error and paired t-test of the MOR of treated ($R = 37.46$ kg m^{-3}) and air dried small clear-wood radiata pine specimens [Chapter 4, Section 4.1, Expt. A].

[Legend: Column 1 = Control; Column 2 = CCA treated]

Source:	df:	Sum of Squares:	Mean Square:	F-test:	P value:
Between subjects	39	3886.771	99.661	1.463	.1178
Within subjects	40	2725.513	68.138		
treatments	1	1692.749	1692.749	63.923	.0001
residual	39	1032.764	26.481		
Total	79	6612.285			

Reliability Estimates for- All treatments: .316 Single Treatment: .188

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
Column 1	40	61.357	7.045	1.114
Column 2	40	70.557	8.747	1.383

Paired t-Test X_1: Column 1 Y_1: Column 2

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
39	-9.2	-7.995	.0001

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
Column 1 vs. Column 2	-9.2	2.328*	63.923*	7.995

* Significant at 95%

ANOVA, means, standard deviation, standard error and paired t-test of the MOR of treated (R = 13.09 kg m^{-3}) and air dried small clear-wood radiata pine specimens [Chapter 4, Section 4.1, Expt. B].

[Legend: Column 1 = Control; Column 2 = CCA treated]

Source:	df:	Sum of Squares:	Mean Square:	F-test:	P value:
Between subjects	29	2423.384	83.565	1.642	.0913
Within subjects	30	1526.683	50.889		
treatments	1	106.02	106.02	2.164	.152
residual	29	1420.663	48.988		
Total	59	3950.067			

Reliability Estimates for- All treatments: .391 Single Treatment: .243

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
Column 1	30	77.217	9.09	1.66
Column 2	30	74.558	7.066	1.29

Paired t-Test X_1: Column 1 Y_1: Column 2

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
29	2.659	1.471	.152

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
Column 1 vs. Column 2	2.659	3.696	2.164	1.471

ANOVA, means, standard deviation, standard error and paired t-test of the MCS of treated ($R = 35.13$ kg m^{-3}) and air dried small clear-wood radiata pine specimens [Chapter 4, Section 4.1, Expt. A].

[Legend: Column 1 = Control; Column 2 = CCA treated]

Source:	df:	Sum of Squares:	Mean Square:	F-test:	P value:
Between subjects	39	1800.771	46.174	2.218	.0069
Within subjects	40	832.707	20.818		
treatments	1	116.55	116.55	6.347	.016
residual	39	716.157	18.363		
Total	79	2633.478			

Reliability Estimates for- All treatments: .549 Single Treatment: .378

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
Column 1	40	43.348	5.521	.873
Column 2	40	40.934	5.835	.923

Paired t-Test X_1: Column 1 Y_1: Column 2

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
39	2.414	2.519	.016

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
Column 1 vs. Column 2	2.414	1.938*	6.347*	2.519

* Significant at 95%

ANOVA, means, standard deviation, standard error and paired t-test of the MCS of treated ($R = 12.27$ kg m^{-3}) and air dried small clear-wood radiata pine specimens [Chapter 4, Section 4.1, Expt. B].

[Legend: Column 1 = Control; Column 2 = CCA treated]

Source:	df:	Sum of Squares:	Mean Square:	F-test:	P value:
Between subjects	29	824.26	28.423	1.045	.452
Within subjects	30	815.964	27.199		
treatments	1	150.597	150.597	6.564	.0159
residual	29	665.367	22.944		
Total	59	1640.225			

Reliability Estimates for- All treatments: .043 Single Treatment: .022

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
Column 1	30	45.374	4.654	.85
Column 2	30	42.206	5.451	.995

Paired t-Test X_1: Column 1 Y_1: Column 2

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
29	3.169	2.562	.0159

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
Column 1 vs. Column 2	3.169	2.53*	6.564*	2.562

* Significant at 95%

ANOVA, means, standard deviation, standard error and paired t-test of the MOE of water treated and re-dried small clear-wood radiata pine specimens [Chapter 4, Section 4.2]

[Legend: Column 1 = Control; Column 2 = Water-treated and air dried; Column 3 = Water-treated and oven dried]

Source:	df:	Sum of Squares:	Mean Square:	F-test:	P value:
Between subjects	25	43807288.356	1752291.534	1.392	.156
Within subjects	52	65464519.033	1258933.058		
treatments	2	15519912.653	7759956.327	7.769	.0012
residual	50	49944606.379	998892.128		
Total	77	109271807.389			

Reliability Estimates for- All treatments: .282 Single Treatment: .116

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
Column 1	26	10298.571	922.17	180.852
Column 2	26	11017.707	1203.488	236.023
Column 3	26	11370.537	1204.697	236.26

Paired t-Test X_1: Column 1 , Y_1: Column 2

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
25	-719.136	-2.483	.0201

Paired t-Test X_1: Column 1 Y_2: Column 3

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
25	-1071.967	-4.109	.0004

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
Column 1 vs. Column 2	-719.136	556.822*	3.365*	2.594
Column 1 vs. Column 3	-1071.967	556.822*	7.478*	3.867
Column 2 vs. Column 3	-352.83	556.822	.81	1.273

* Significant at 95%

ANOVA, means, standard deviation, standard error and paired t-test of the MOR of water treated and re-dried small clear-wood radiata pine specimens [Chapter 4, Section 4.2]

[Legend: Column 1 = Control; Column 2 = Water-treated and air dried; Column 3 = Water-treated and oven dried]

Source:	df:	Sum of Squares:	Mean Square:	F-test:	P value:
Between subjects	25	2703.02	108.121	1.839	.0322
Within subjects	52	3057.209	58.792		
treatments	2	169.462	84.731	1.467	.2404
residual	50	2887.747	57.755		
Total	77	5760.229			

Reliability Estimates for- All treatments: .456 Single Treatment: .219

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
Column 1	26	87.032	8.068	1.582
Column 2	26	83.522	6.93	1.359
Column 3	26	86.011	10.513	2.062

Paired t-Test X_1: Column 1 Y_1: Column 2

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
25	3.51	1.769	.0891

Paired t-Test X_1: Column 1 Y_2: Column 3

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
25	1.021	.446	.6591

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
Column 1 vs. Column 2	3.51	4.234	1.386	1.665
Column 1 vs. Column 3	1.021	4.234	.117	.484
Column 2 vs. Column 3	-2.489	4.234	.697	1.181

ANOVA, means, standard deviation, standard error and paired t-test of the MCS of water treated and re-dried small clear-wood radiata pine specimens [Chapter 4, Section 4.2]

[Legend: Column 1 = Control; Column 2 = Water-treated and air dried; Column 3 = Water-treated and oven dried]

Source:	df:	Sum of Squares:	Mean Square:	F-test:	P value:
Between subjects	25	841.191	33.648	1.778	.0403
Within subjects	52	984.01	18.923		
treatments	2	28.038	14.019	.733	.4854
residual	50	955.972	19.119		
Total	77	1825.201			

Reliability Estimates for- All treatments: .438 Single Treatment: .206

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
Column 1	26	49.066	5.682	1.114
Column 2	26	47.646	3.722	.73
Column 3	26	48.031	5.075	.995

Paired t-Test X_1: Column 1 Y_1: Column 2

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
25	1.42	1.23	.2303

Paired t-Test X_1: Column 1 Y_2: Column 3

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
25	1.035	.677	.5044

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
Column 1 vs. Column 2	1.42	2.436	.685	1.171
Column 1 vs. Column 3	1.035	2.436	.364	.853
Column 2 vs. Column 3	-.385	2.436	.05	.317

ANOVA, means, standard deviation, standard error and paired t-test of the MOE of oven dried small clear-wood radiata pine specimens [Chapter 4, Section 4.3]

[Legend: Column 1 = Control; Column 2 = Oven dried]

Source:	df:	Sum of Squares:	Mean Square:	F-test:	P value:
Between subjects	24	120661859.151	5027577.465	1.419	.1952
Within subjects	25	88575410.165	3543016.407		
treatments	1	5396014.237	5396014.237	1.557	.2242
residual	24	83179395.928	3465808.164		
Total	49	209237269.316			

Reliability Estimates for- All treatments: .295 Single Treatment: .173

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
Column 1	25	10291.73	2224.053	444.811
Column 2	25	10948.754	1883.341	376.668

Paired t-Test X_1: Column 1 Y_1: Column 2

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
24	-657.024	-1.248	.2242

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
Column 1 vs. Column 2	-657.024	1086.88	1.557	1.248

ANOVA, means, standard deviation, standard error and paired t-test of the MOR of oven dried small clear-wood radiata pine specimens [Chapter 4, Section 4.3]

[Legend: Column 1 = Control; Column 2 = Oven dried]

Source:	df:	Sum of Squares:	Mean Square:	F-test:	P value:
Between subjects	24	6170.912	257.121	1.754	.0849
Within subjects	25	3664.404	146.576		
treatments	1	1100.681	1100.681	10.304	.0037
residual	24	2563.723	106.822		
Total	49	9835.316			

Reliability Estimates for- All treatments: .43 Single Treatment: .274

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
Column 1	25	90.762	12.284	2.457
Column 2	25	100.145	14.596	2.919

Paired t-Test X_1: Column 1 Y_1: Column 2

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
24	-9.384	-3.21	.0037

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
Column 1 vs. Column 2	-9.384	6.034*	10.304*	3.21

* Significant at 95%

ANOVA, means, standard deviation, standard error and paired t-test of the MCS of oven dried small clear-wood radiata pine specimens [Chapter 4, Section 4.3]

[Legend: Column 1 = Control; Column 2 = Oven dried]

Source:	df:	Sum of Squares:	Mean Square:	F-test:	P value:
Between subjects	24	2568.283	107.012	3.749	.0008
Within subjects	25	713.55	28.542		
treatments	1	332.502	332.502	20.942	.0001
residual	24	381.048	15.877		
Total	49	3281.833			

Reliability Estimates for- All treatments: .733 Single Treatment: .579

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
Column 1	25	48.577	8.484	1.697
Column 2	25	53.734	7.136	1.427

Paired t-Test X_1: Column 1 Y_1: Column 2

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
24	-5.158	-4.576	.0001

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
Column 1 vs. Column 2	-5.158	2.326*	20.942*	4.576

* Significant at 95%

ANOVA, means, standard deviation, standard error and paired t-test of the MOE of treated and high temperature dried small clear-wood radiata pine specimens [Chapter 5]

[Legend: Column 1 = Control; Column 2 = Water-treated; Column 3 = CCA treated Low-retention; Column 4 = CCA treated High-retention]

Source:	df:	Sum of Squares:	Mean Square:	F-test:	P value:
Between subjects	44	1135537066.21	25807660.596	14.191	.0001
Within subjects	135	245510903.26	1818599.283		
treatments	3	2868988.27	956329.423	.52	.6691
residual	132	242641914.99	1838196.326		
Total	179	1381047969.47			

Reliability Estimates for- All treatments: .93 Single Treatment: .767

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
Column 1	45	10209.814	2831.488	422.093
Column 2	45	10116.393	2649.724	394.998
Column 3	45	9886.063	2707.569	403.621
Column 4	45	10175.473	2992.149	446.043

Paired t-Test X_1: Column 1 Y_1: Column 2

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
44	93.421	.354	.725

Paired t-Test X_1: Column 1 Y_2: Column 3

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
44	323.75	1.178	.2451

Paired t-Test X_1: Column 1 Y_3: Column 4

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
44	34.341	.13	.8969

Paired t-Test X_1: Column 2 Y_1: Column 3

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
44	230.33	.801	.4272

Paired t-Test X_1: Column 2 Y_2: Column 4

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
44	-59.08	-.183	.8553

Paired t-Test X_1: Column 3 Y_1: Column 4

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
44	-289.41	-.969	.338

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
Column 1 vs. Column 2	93.421	565.452	.036	.327
Column 1 vs. Column 3	323.75	565.452	.428	1.133
Column 1 vs. Column 4	34.341	565.452	.005	.12
Column 2 vs. Column 3	230.33	565.452	.216	.806
Column 2 vs. Column 4	-59.08	565.452	.014	.207
Column 3 vs. Column 4	-289.41	565.452	.342	1.013

ANOVA, means, standard deviation, standard error and paired t-test of the MOR of treated and high temperature dried small clear-wood radiata pine specimens [Chapter 5]

[Legend: Column 1 = Control; Column 2 = Water-treated; Column 3 = CCA treated Low-retention; Column 4 = CCA treated High-retention]

Source:	df:	Sum of Squares:	Mean Square:	F-test:	P value:
Between subjects	43	32284.414	750.8	3.508	.0001
Within subjects	132	28247.37	213.995		
treatments	3	15049.567	5016.522	49.033	.0001
residual	129	13197.803	102.309		
Total	175	60531.783			

Reliability Estimates for- All treatments: .715 Single Treatment: .385

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
Column 1	44	60.914	19.418	2.927
Column 2	44	61.813	16.798	2.532
Column 3	44	42.034	14.236	2.146
Column 4	44	43.811	13.994	2.11

Paired t-Test X_1: Column 1 Y_1: Column 2

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
43	-.899	-.481	.6328

Paired t-Test X_1: Column 1 Y_2: Column 3

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
43	18.88	8.481	.0001

Paired t-Test X_1: Column 1 Y_3: Column 4

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
43	17.102	7.198	.0001

Paired t-Test X_1: Column 2 Y_1: Column 3

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
43	19.779	9.374	.0001

Paired t-Test X_1: Column 2 Y_2: Column 4

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
43	18.001	7.411	.0001

Paired t-Test X_1: Column 3 Y_1: Column 4

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
43	-1.777	-.956	.3446

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
Column 1 vs. Column 2	-.899	4.267	.058	.417
Column 1 vs. Column 3	18.88	4.267*	25.549*	8.755
Column 1 vs. Column 4	17.102	4.267*	20.965*	7.931
Column 2 vs. Column 3	19.779	4.267*	28.041*	9.172
Column 2 vs. Column 4	18.001	4.267*	23.228*	8.348
Column 3 vs. Column 4	-1.777	4.267	.226	.824

* Significant at 95%

ANOVA, means, standard deviation, standard error and paired t-test of the MCS of treated and high temperature dried small clear-wood radiata pine specimens [Chapter 5]

[Legend: Column 1 = Control; Column 2 = Water-treated; Column 3 = CCA treated Low-retention; Column 4 = CCA treated High-retention]

Source:	df:	Sum of Squares:	Mean Square:	F-test:	P value:
Between subjects	47	9541.521	203.011	5.075	.0001
Within subjects	144	5760.458	40.003		
treatments	3	622.795	207.598	5.697	.001
residual	141	5137.663	36.437		
Total	191	15301.979			

Reliability Estimates for- All treatments: .803 Single Treatment: .505

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
Column 1	48	41.425	8.553	1.235
Column 2	48	42.081	9.039	1.305
Column 3	48	45.505	9.044	1.305
Column 4	48	45.124	8.699	1.256

Paired t-Test X_1: Column 1 Y_1: Column 2

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
47	-.656	-.475	.6367

Paired t-Test X_1: Column 1 Y_2: Column 3

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
47	-4.081	-3.316	.0018

Paired t-Test X_1: Column 1 Y_3: Column 4

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
47	-3.699	-3.372	.0015

Paired t-Test X_1: Column 2 Y_1: Column 3

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
47	-3.425	-3.013	.0042

Paired t-Test X_1: Column 2 Y_2: Column 4

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
47	-3.043	-2.297	.0261

Paired t-Test X_1: Column 3 Y_1: Column 4

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
47	.382	.318	.7519

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
Column 1 vs. Column 2	-.656	2.436	.094	.532
Column 1 vs. Column 3	-4.081	2.436*	3.656*	3.312
Column 1 vs. Column 4	-3.699	2.436*	3.004*	3.002
Column 2 vs. Column 3	-3.425	2.436*	2.575	2.779
Column 2 vs. Column 4	-3.043	2.436*	2.033	2.47
Column 3 vs. Column 4	.382	2.436	.032	.31

* Significant at 95%

ANOVA, means, standard deviation, standard error and paired t-test of the MOE of treated and high temperature dried structural size radiata pine specimens [Chapter 6]

[Legend: Column 1 = Control; Column 2 = Water-treated; Column 3 = CCA treated Low-retention; Column 4 = CCA treated High-retention]

Source:	df:	Sum of Squares:	Mean Square:	F-test:	P value:
Between subjects	55	1.211E9	22024057.403	11.802	.0001
Within subjects	168	313508021.663	1866119.177		
treatments	3	277399.801	92466.6	.049	.9857
residual	165	313230621.862	1898367.405		
Total	223	1524831178.85			

Reliability Estimates for- All treatments: .915 Single Treatment: .73

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
Column 1	56	9897.962	2502.4	334.397
Column 2	56	9827.295	2750.731	367.582
Column 3	56	9808.651	2796.093	373.644
Column 4	56	9818.451	2464.244	329.298

Paired t-Test X_1: Column 1 Y_1: Column 2

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
55	70.667	.273	.7856

Paired t-Test X_1: Column 1 Y_2: Column 3

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
55	89.311	.399	.6917

Paired t-Test X_1: Column 1 Y_3: Column 4

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
55	79.511	.336	.7383

Paired t-Test X_1: Column 2 Y_1: Column 3

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
55	18.645	.064	.9494

Paired t-Test X_1: Column 2 Y_2: Column 4

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
55	8.844	.032	.9746

Paired t-Test X_1: Column 3 Y_1: Column 4

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
55	-9.8	-.037	.9709

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
Column 1 vs. Column 2	70.667	514.161	.025	.271
Column 1 vs. Column 3	89.311	514.161	.039	.343
Column 1 vs. Column 4	79.511	514.161	.031	.305
Column 2 vs. Column 3	18.645	514.161	.002	.072
Column 2 vs. Column 4	8.844	514.161	3.846E-4	.034
Column 3 vs. Column 4	-9.8	514.161	4.722E-4	.038

ANOVA, means, standard deviation, standard error and paired t-test of the MOR of treated and high temperature dried structural size radiata pine specimens [Chapter 6]

[Legend: Column 1 = Control; Column 2 = Water-treated; Column 3 = CCA treated Low-retention; Column 4 = CCA treated High-retention]

Source:	df:	Sum of Squares:	Mean Square:	F-test:	P value:
Between subjects	55	28385.767	516.105	3.837	.0001
Within subjects	168	22598.296	134.514		
treatments	3	6911.957	2303.986	24.235	.0001
residual	165	15686.34	95.069		
Total	223	50984.063			

Reliability Estimates for- All treatments: .739 Single Treatment: .415

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
Column 1	56	37.717	14.701	1.965
Column 2	56	35.848	16.056	2.146
Column 3	56	27.079	13.644	1.823
Column 4	56	24.685	11.884	1.588

Paired t-Test X_1: Column 1 Y_1: Column 2

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
55	1.869	.932	.3552

Paired t-Test X_1: Column 1 Y_2: Column 3

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
55	10.638	5.637	.0001

Paired t-Test X_1: Column 1 Y_3: Column 4

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
55	13.032	6.421	.0001

Paired t-Test X_1: Column 2 Y_1: Column 3

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
55	8.769	4.772	.0001

Paired t-Test X_1: Column 2 Y_2: Column 4

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
55	11.163	7.294	.0001

Paired t-Test X_1: Column 3 Y_1: Column 4

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
55	2.394	1.393	.1693

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
Column 1 vs. Column 2	1.869	3.639	.343	1.014
Column 1 vs. Column 3	10.638	3.639*	11.11*	5.773
Column 1 vs. Column 4	13.032	3.639*	16.673*	7.072
Column 2 vs. Column 3	8.769	3.639*	7.549*	4.759
Column 2 vs. Column 4	11.163	3.639*	12.233*	6.058
Column 3 vs. Column 4	2.394	3.639	.563	1.299

* Significant at 95%

ANOVA, means, standard deviation, standard error and paired t-test of the MOE of treated and low temperature dried structural size radiata pine specimens [Chapter 7]

[Legend: Column 1 = Control; Column 2 = Water-treated; Column 3 = CCA treated and air dried; Column 4 = CCA treated and kiln dried]

Source:	df:	Sum of Squares:	Mean Square:	F-test:	P value:
Between subjects	55	521206090.42	9476474.371	12.611	.0001
Within subjects	168	126239229.925	751423.988		
treatments	3	51195826.221	17065275.407	37.522	.0001
residual	165	75043403.704	454808.507		
Total	223	647445320.345			

Reliability Estimates for- All treatments: .921 Single Treatment: .744

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
Column 1	56	9954.486	1638.987	219.019
Column 2	56	10468.698	1645.679	219.913
Column 3	56	11117.674	1601.01	213.944
Column 4	56	9954.237	1697.978	226.902

Paired t-Test X_1: Column 1 Y_1: Column 2

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
55	-514.212	-4.326	.0001

Paired t-Test X_1: Column 1 Y_2: Column 3

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
55	-1163.188	-9.668	.0001

Paired t-Test X_1: Column 1 Y_3: Column 4

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
55	.249	.002	.9983

Paired t-Test X_1: Column 2 Y_1: Column 3

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
55	-648.975	-4.632	.0001

Paired t-Test X_1: Column 2 Y_2: Column 4

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
55	514.461	4.006	.0002

Paired t-Test X_1: Column 3 Y_1: Column 4

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
55	1163.437	8.57	.0001

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
Column 1 vs. Column 2	-514.212	251.665*	5.426*	4.035
Column 1 vs. Column 3	-1163.188	251.665*	27.766*	9.127
Column 1 vs. Column 4	.249	251.665	1.270E-6	.002
Column 2 vs. Column 3	-648.975	251.665*	8.643*	5.092
Column 2 vs. Column 4	514.461	251.665*	5.431*	4.037
Column 3 vs. Column 4	1163.437	251.665*	27.778*	9.129

* Significant at 95%

ANOVA, means, standard deviation, standard error and paired t-test of the MOR of treated and low temperature dried structural size radiata pine specimens [Chapter 7]

[Legend: Column 1 = Control; Column 2 = Water-treated; Column 3 = CCA treated and air dried; Column 4 = CCA treated and kiln dried]

Source:	df:	Sum of Squares:	Mean Square:	F-test:	P value:
Between subjects	55	17761.244	322.932	2.466	.0001
Within subjects	168	22002.548	130.968		
treatments	3	3392.564	1130.855	10.026	.0001
residual	165	18609.983	112.788		
Total	223	39763.792			

Reliability Estimates for- All treatments: .594 Single Treatment: .268

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
Column 1	56	33.704	11.754	1.571
Column 2	56	39.076	13.115	1.753
Column 3	56	42.988	14.122	1.887
Column 4	56	33.81	12.317	1.646

Paired t-Test X_1: Column 1 Y_1: Column 2

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
55	-5.371	-2.877	.0057

Paired t-Test X_1: Column 1 Y_2: Column 3

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
55	-9.284	-4.427	.0001

Paired t-Test X_1: Column 1 Y_3: Column 4

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
55	-.106	-.06	.9521

Paired t-Test X_1: Column 2 Y_1: Column 3

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
55	-3.913	-1.836	.0718

Paired t-Test X_1: Column 2 Y_2: Column 4

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
55	5.266	2.671	.0099

Paired t-Test X_1: Column 3 Y_1: Column 4

DF:	Mean X - Y:	Paired t value:	Prob. (2-tail):
55	9.178	4.204	.0001

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
Column 1 vs. Column 2	-5.371	3.963*	2.388	2.676
Column 1 vs. Column 3	-9.284	3.963*	7.133*	4.626
Column 1 vs. Column 4	-.106	3.963	.001	.053
Column 2 vs. Column 3	-3.913	3.963	1.267	1.949
Column 2 vs. Column 4	5.266	3.963*	2.294	2.624
Column 3 vs. Column 4	9.178	3.963*	6.971*	4.573

* Significant at 95%